VOLUME 103 PART B NUMBER 11 SEPTEMBER 1956

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

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PART B

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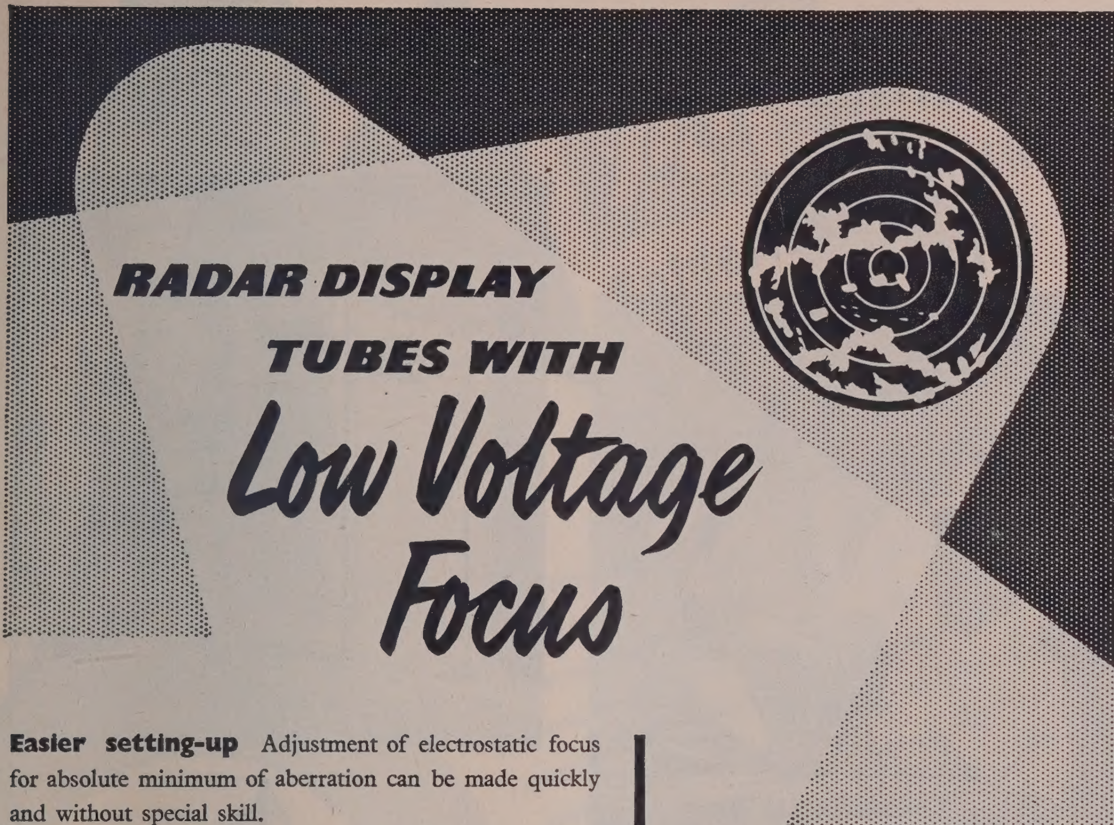

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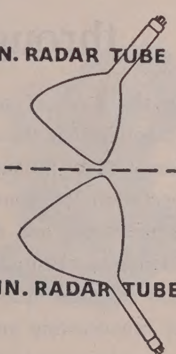

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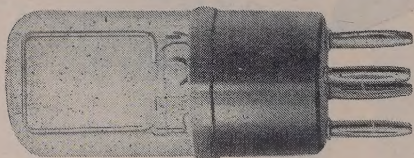

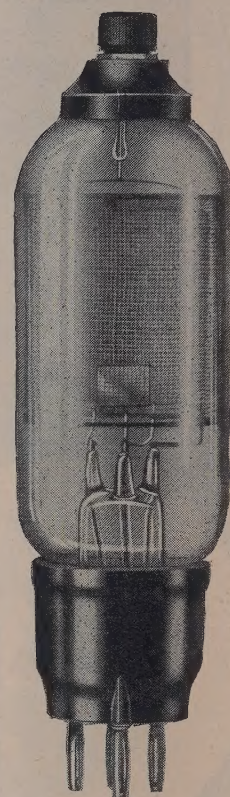

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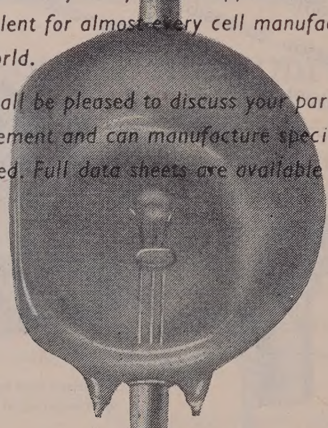

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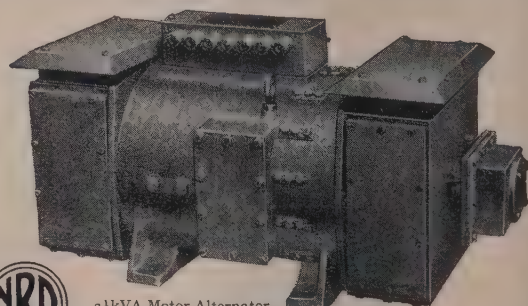

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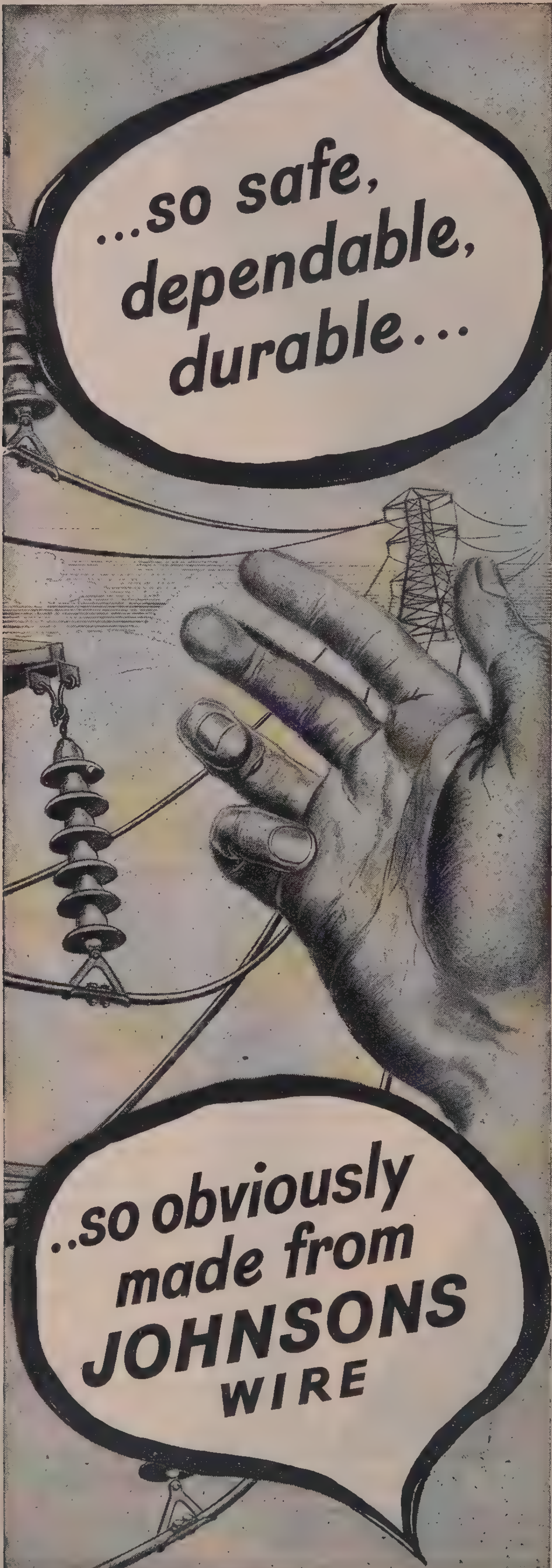

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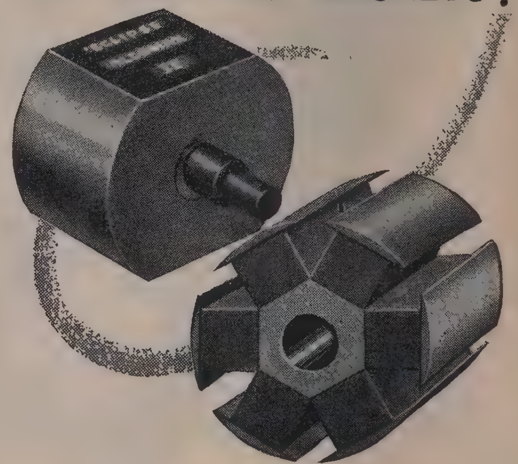

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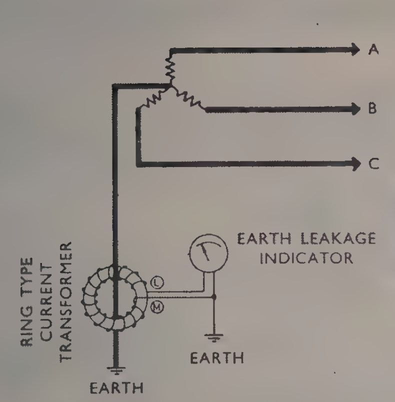

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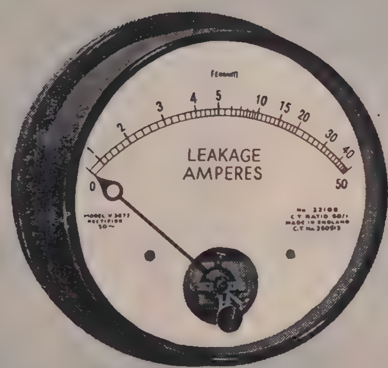

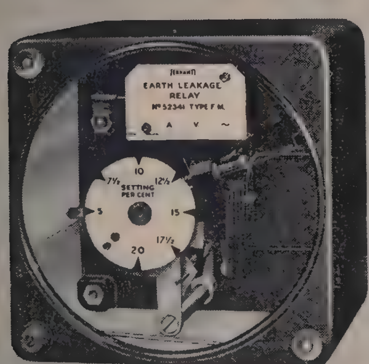

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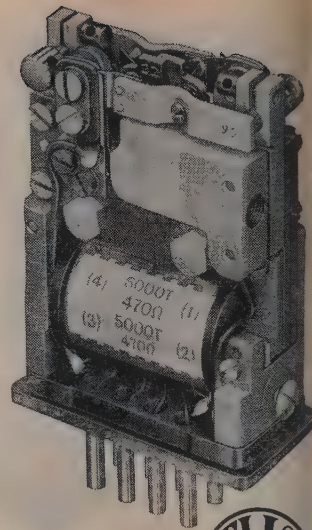

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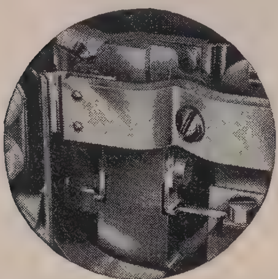

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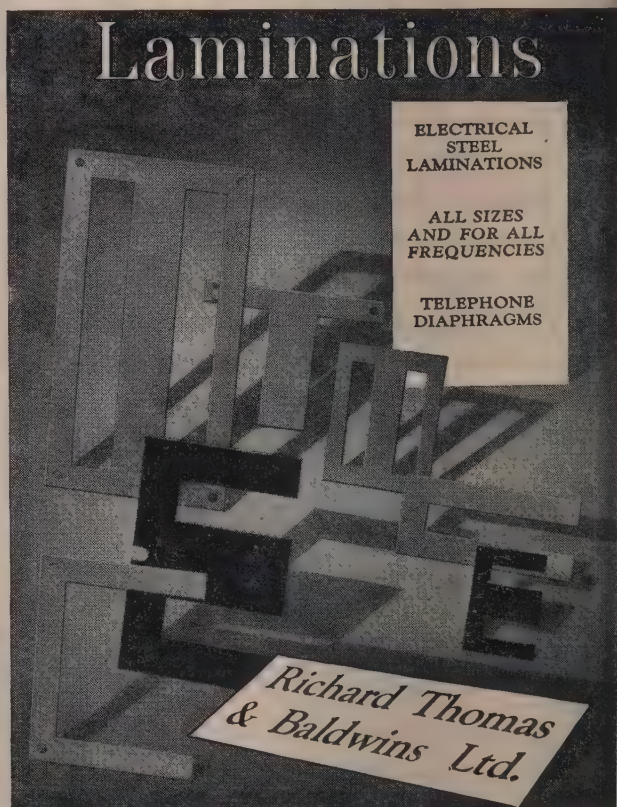

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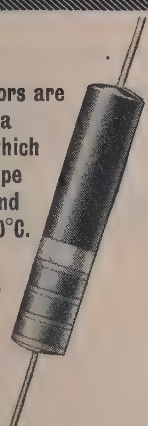

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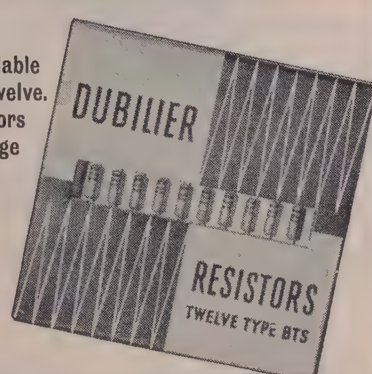

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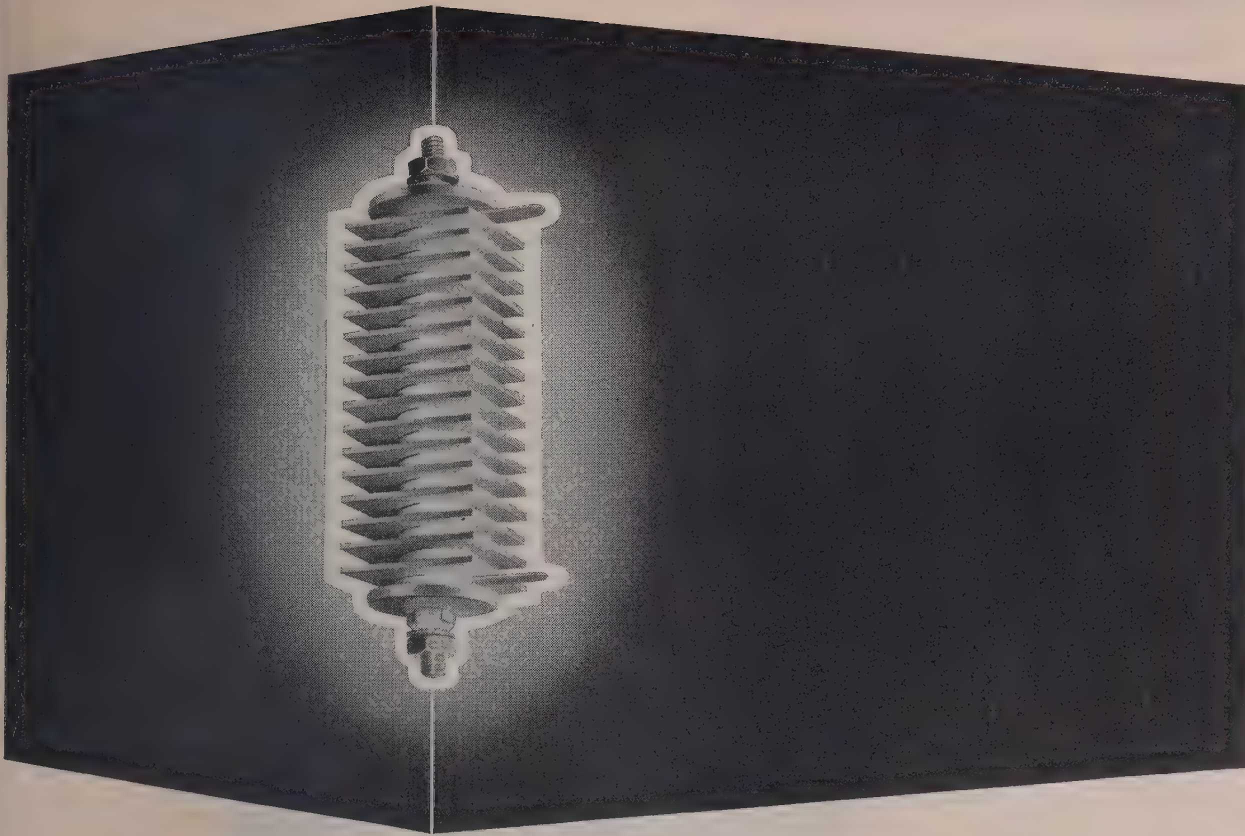

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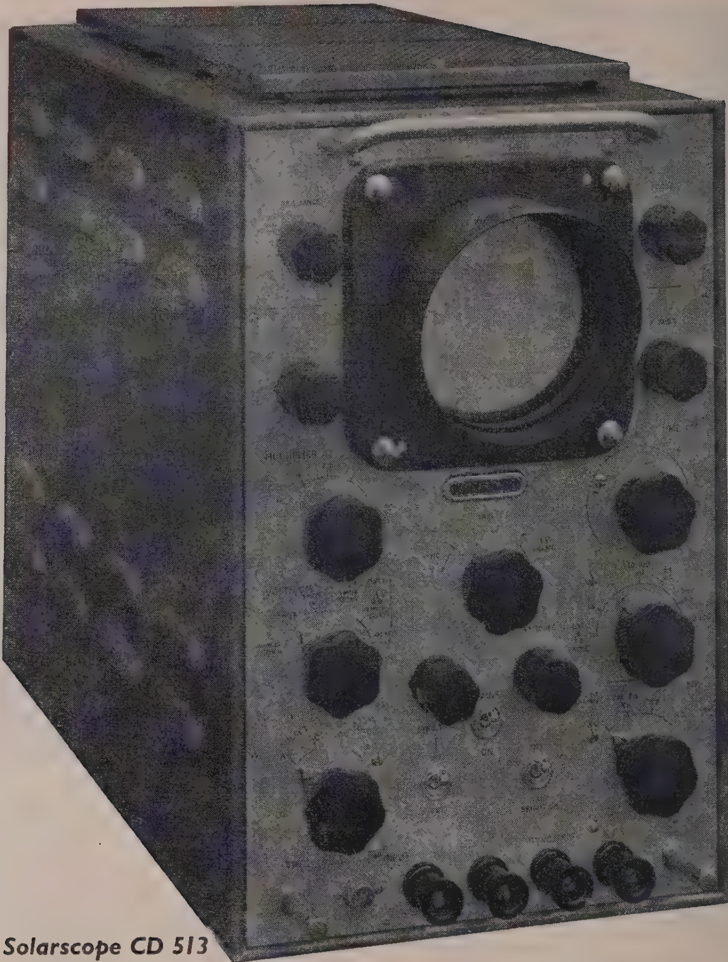

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VOL. 103. PART B. No. 11. SEPTEMBER 1956

Abstract No. 2117
June 1956

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By E. WILKINSON, Ph.D., B.Eng., Member.

"STRAW FOR THE BRICKS"

(ABSTRACT *of Address delivered at* ABERDEEN *7th March, and* DUNDEE *8th March*, 1956.)

It is hardly necessary to restate the need for expansion of the cilities for technical education and training, and the purpose this address is rather to examine the means by which an adeiate number of university and college entrants with suitable ialifications may be found, especially in Scotland.

Previous University Expansion

In the universities throughout the country there has already en considerable expansion since the war, and the technological ıdent population has about doubled. Sufficient time has now apsed, since this expansion occurred, to make an estimate of its ıalitative success worth while. This may be done in various ays.

The quality of graduates may be assessed by comparing the oportion gaining honours degrees in technology to those staining pass degrees. In 1939 this ratio was 1·04. In 1952, spite of larger classes, the ratio rose to 1·4 and remained about that figure for the following years. In addition ere was an appreciably higher proportion of success in postaduate study. Taking this evidence at its face value, one can ly conclude that quality has improved as well as quantity. ıe evidence must, however, be taken with caution because the creased numbers taking the longer honours or additional urses cannot be entirely dissociated from the more liberal ıancial support now available for continued study.

Some statistics of bursary awards in Scotland show that in one cent year there were 1 573 first awards to universities and that 0 were terminated because of unsatisfactory progress. The ilure ratio was as high as 29·6% for boys and 16·4% for girls. wards were also made for attendance at central institutions, ıere the stricter educational and marking discipline reduced e wastage by a factor of about three. Evidently there are any students who, although qualified, are either unable or ıwilling to perform the work of the courses.

The Report of the Committee on Scientific Manpower, ıblished late in 1955, put forward the views of industry on the ıality of the graduate output, and many of those consulted pressed criticism of the candidates they had interviewed. The Report summed up these criticisms in rather non-committal terms without denying them.

It may reasonably be concluded from this and other evidence that further expansion cannot be achieved by an arbitrary lowering of entry standards, without endangering the quality of graduates from existing courses. This does not, however, preclude the possibility of changing the entry conditions or even of lowering them if, in suitably planned courses, the deficiencies can be made up.

The School Output in Scotland

Table 1 shows the successes gained in 1954 in the Scottish Leaving Certificate. In order to satisfy the requirements of university entrance, a candidate must have either four higher passes or three 'highers' and two 'lowers'. If the fact that entry to specific study also depends upon having passes in the right subjects be ignored then 2 836 qualify. The number of those who are deficient in only one subject amounts to 1 376, or nearly 50% as many as the qualifiers. These must be considered as potential recruits to technical or other courses.

Table 1

SCOTTISH LEAVING CERTIFICATE. PASSES IN 1954

Higher grade ↓ / Lower grade → (Number of subjects)	0	1	2	3	4	5
0		224	252	169	106	25
1	87	233	361	340	135	12
2	61	239	**477**	**451**	**83**	**1**
3	**55**	**309**	655	219	5	—
4	84	499	346	27	1	—
5	296	537	148	18	1	—

Satisfactory, 2 836. Nearly satisfactory, **1376**. Not satisfactory, 2 244.

There were 2 854 entrants to Scottish universities in 1953, and the similarity of this figure to the number of qualifiers illustrates the known fact that there is not much wastage at this stage. The wastage occurs earlier, at 15 or 16 years of age.

There appear to be three ways of increasing the available entry of boys to technological courses:

(i) By ensuring that fewer able schoolboys leave school at an early age.

Dr. Wilkinson is Head of the Electrical Department at Robert Gordon's College, erdeen.

(ii) By diverting talent which would otherwise pass into different educational streams, such as the arts.
(iii) By making use of candidates of slightly poorer qualifications and supplementing their preliminary education where necessary.

The first two of these may be achieved by an intensification of the information services, including personal contacts, printed pamphlets, films and television, which should not only inform the schoolboys of the careers from which they may select but also start them correctly on the right road. There is still inadequate knowledge that the engineering profession offers a life of great interest and unlimited scope. The view that reading the history of past civilizations is necessarily of more cultural significance than writing that of the present or planning that of the future needs to be dispelled.

Recruitment to Universities

During the academic year 1952–53 and the following year there were about 14 000 registered students in Scottish universities, or 0·28% of the population of the country. In England during the same two years there were about 62 400 students attending the universities, or only 0·16% of the population. Scotland may claim to be 75% ahead of England in providing places, and the ratio is even higher when the comparison is limited to technology.

It is also of interest to compare the efficiency with which the native raw material is used. Of those born in England in 1935, about 2·72% survived to enter a university about 18 years later, while in Scotland about 3·25% succeeded in doing so.

An analysis of the 1952 entry to Scottish universities demonstrates that the four chief cities sent 3·3% of their age groups to the university; the mainly industrial areas, only 1·9%; the mixed industrial and rural areas, 2·5%; and the rural areas, 4·1%. Those in outlying districts are apparently well aware of the educational facilities, though the proportion of engineering students from these areas is small. The proportion entering the faculty of arts was almost identical from all four areas, being about 43%. The 'technologies' account for the following proportions of the respective groups: 24·2%, 21·8%, 21·3% and 17·6%. The rural areas offer fewer students of technology, and, since agriculture and forestry are included in the total and may be expected to predominate, few remain for engineering. It is interesting to note that, in contrast, the rural areas provided the highest proportion of pure scientists, the figures being respectively 15·9%, 16·4%, 23·1% and 24·9%.

The small entry from the industrial areas is noteworthy. It is perhaps to be expected that, when local employers offer sufficient vacancies, a boy may be tempted to start work direct from school instead of continuing his studies.

The same symptom appears when figures relating the student population of various universities to the population of the university city are considered. The number of 'local students', i.e. those whose homes are within 30 miles of the university compared with the population of the city itself, is very low for certain industrial towns. Thus, while Edinburgh and Aberdeen provide 4·7 local students per 1 000 of the population, Cambridge 3·9 and Oxford 3·0, yet Bristol accounts for only 1·8, Nottingham 1·3 and Birmingham 1·1.

It has been suggested that perhaps 4 000 early-leavers from school would benefit by staying to take advanced courses in mathematics and science. Reviews such as these help to show where some of the talent may be found and where encouragement might usefully be given.

Women as Engineers

There is a possibility which has hardly been mentioned in this country. In the past, recruitment of women to the engineering profession has been virtually negligible, but a good case can be made out for their employment. Very few girls have studied with the object of becoming engineers, and of these many have left industry on marrying. Many engineering posts could well be filled by women, who are potentially good material to train as engineers. The statistics of bursary holders at university and college show that their performance is in one respect better than that of the men.

Their performance in the Scottish Leaving Certificate and the General Certificate of Education also compares favourably with that of the boys. It may be noted, however, that relatively few girls pursue a scientific higher school education. It is reasonable to suggest that this arises from the limited opportunities available in the past and ignorance of the possibilities which the future may hold, perhaps especially in the engineering office and the development laboratory.

If women are to be successfully employed as engineers there must be a minor social revolution to encourage many of them to continue work after marriage, since only thus is their training economically justifiable. Blocks of service flats, fully equipped with modern labour-saving devices, might offer one form of practical encouragement. The scale of financial rewards and advancement could also be designed in various ways to encourage continued working.

Early School-Leavers

Some of the early school-leavers commence an apprenticeship and enter part-time National Certificate Courses. In the past this has been a recognized and popular method of qualifying for membership of the professional institutions. The courses of study leading to membership of our own Institution have now been extended, and a purely part-time education can no longer be regarded as satisfactory, since it would take far too long. It is to be expected, therefore, that those with ability will seek transfer to alternative courses.

Universities could well consider accepting a high-level pass in the Ordinary National Certificate as a suitable entrance qualification. Entry at Higher National Certificate level hardly seems to be wise, since those who have reached this standard are already virtually a finished product and the university largely reprocesses the student to reach a similar standard. On the other hand, a bare pass at Ordinary Certificate level is not satisfactory since this appears to be the ceiling of attainment of so many. At present only about one-third of the candidates for the Ordinary Certificate successfully proceed to the Higher Certificate Course.

National Service

There is another way of increasing forthwith the usefulness of our young technologists, namely by granting complete exemption from National Service to those who have graduated from college or university courses. Neither the Services nor the engineer in training appear to benefit greatly from the present arrangement, and training for industry is severely handicapped.

University or College Courses

It may fairly be assumed that, in some or all of these ways, increased numbers of trainees may be forthcoming. Not all of them will attend universities, and many will proceed to central institutions. The Higher National Diploma Courses no longer meet the new requirements of The Institution, without considerable modification. These courses were originally intended for entrants from industry, but they have largely been supported by school-leavers who have narrowly failed to qualify for a university course. There is every reason now for such schoolboys to be encouraged to remain at school until they have completed their university entrance qualification.

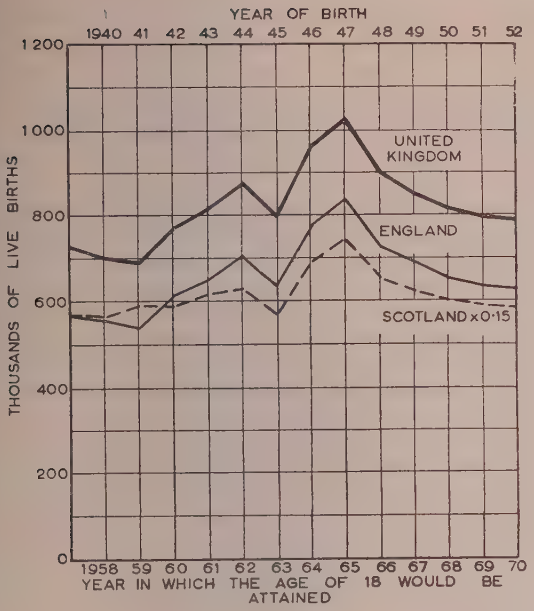

Fig. 1

In England there is now a general agreement that six-month sandwich courses lasting 4–5 years have special merit, and the system has already been widely adopted by the larger concerns. It is to be hoped that a high standard of entrance can be set, perhaps even as high as for university entrance. The prospects for sandwich courses of a similar kind are not so bright in Scotland. First, far more of the prospective students are already provided for in universities than in England. Secondly, the adolescent population is increasing at a slower rate. The 'bulge' is relatively smaller in Scotland, and the birth rate seems to have settled down at a level about 7% below that in England on a scale assuming parity eighteen years ago (see Fig. 1).

There are no electrical or mechanical industries in Scotland on the scale of those in England and covering such a wide range of manufactured products, but there are a number of first-rate firms, most of which already run apprenticeship schemes for graduates and others. Very recently these firms have formed a committee to plan a broader training course, offering widely varied experience by a pooling of their facilities. An apprentice who has had experience in a number of these establishments should be adequately trained, and a Certificate of Apprenticeship, vouched for by the Scottish Electrical Industries Training Scheme, should rank high. Indeed it may be hoped that action by this Committee may induce a few more Scots to take up engineering.

If a sandwich scheme were launched in Scotland on the English model it would provide an opportunity for National Certificate students and for some of those who, in the past, would have taken a three-year Higher National Diploma Course.

The advantages of a university course in respect of breadth of study suggest that every effort should be made to ensure that, if a student is likely to benefit by a university education, he should be admitted. At present every student who wishes to enter a Scottish University must have passed in English at the higher level, whatever he proposes to study, and this requires a knowledge of literature. It will be generally agreed that a command of English is essential for an engineering graduate, but it is surely unreasonable to require a knowledge of literature as a condition of entry to a science faculty. It would be more logical for the Scottish Universities Entrance Board and The Institution, whose demands are the same, to limit their requirements to a pass in the English Language paper alone.

This has been a critical appraisal of the material with which the industrial Britain of the future must be built, and particularly of the contribution to be made by Scotland. Britain cannot afford to lag behind its competitors in technological recruitment, and any proposals which may assist, even partly, in solving the problems of education and training merit serious consideration.

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THE CONTROL AND INSTRUMENTATION OF A NUCLEAR REACTOR

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SUMMARY

The control and instrumentation of nuclear reactors is a rapidly developing subject which is becoming of ever-increasing importance to a growing body of instrument engineers. Many of the problems of instrumental design are common with other industrial plants and follow conventional lines. Some, however, are more specialized, and arise principally from the radioactive nature of the reactor and its unusual dynamic behaviour. The paper presents a survey of the overall instrumentation of a typical research reactor. Emphasis is placed on the less-well-known problems of measurement and control, and to assist in their understanding a brief account is given of the mode of operation of a nuclear reactor, and a short Section on reactor kinetics is also included. The types of instruments in present-day use are described, and indications are given of their shortcomings. New developments are briefly reviewed. The paper concludes with a Section on reactor safety. The philosophy of safety-circuit design is outlined, and examples are given of instruments and circuits which conform to this basic code and which have been used on a number of experimental reactors at Harwell.

LIST OF PRINCIPAL SYMBOLS

τ = Mean lifetime of neutron in chain-reacting system.
K_{eff} = Reproduction factor of reacting system of finite size.
K_∞ = Reproduction factor of theoretical infinite assembly.
n = Number of neutrons per unit volume.
S = Number of neutrons added per second per unit volume by spontaneous fission or artificial sources.
ρ = Reactivity $[(K_{eff} - 1)/K_{eff}]$.
N = Neutron density at time $t = 0$.
β = Proportion of fission neutrons which are delayed (0·0076 in a uranium system).
λ_i = Decay constant of nuclei of the ith group.
r_i = Density of i-type nuclei present.
c_i = Fraction of neutrons present producing i-type nuclei.
A_s = Constant representing the relative amplitude of the sth term in the solution of the reactor kinetic equations.
μ_s = Decay constant of the sth term.
A_0 = Value of A_s when $s = 0$.
μ_0 = Value of μ_s when $s = 0$ (defined as the reciprocal of reactor period).
I = Diode current.
I_0 = Diode current corresponding to zero voltage.
e = Electronic charge.
V = Diode voltage.
k = Boltzmann's constant.
T = Absolute temperature of cathode.
G = Valve amplification factor.
P_t = Power level at time t.
P_0 = Power level at time $t = 0$.

(1) INTRODUCTION

Much has been written about the design and operation of nuclear reactors.[1,2] Some of the specialized aspects of control and instrumentation have also been described in detail in the literature,[3] but the overall problem of instrumenting a reactor is one which does not appear to have received attention in this way. In the paper it is proposed to discuss this problem and to describe the various types of instrument used, particular attention being given to the less-well-known nuclear measuring instruments.

Before the instrumentation proper is discussed, it is desirable to include a short explanation of the mode of operation of a nuclear reactor, together with a few elements of reactor kinetics.

Most nuclear reactors consist of a central core of fissile material, which supports the neutron-propagated nuclear-fission chain reaction, together with a number of movable mechanical elements, either within the core or just outside it, which provide the necessary facilities for maintaining the reaction under control. A thermal reactor is one in which the neutrons born in fission are slowed down to thermal velocities by a moderating material, such as graphite or heavy water, before producing further fissions. A reactor fuelled with natural uranium is a member of this class. Natural uranium contains only 0·7% of the fissile isotope uranium 235, and this has a much greater probability of fission by thermal neutrons than by fast ones. In fact, in a natural-uranium reactor the chain reaction can be achieved only by efficient slowing down of the neutrons, since the uranium 238 which forms the bulk of the fuel captures a substantial proportion of the neutrons without undergoing fission.

A fast reactor uses no moderator and its chain reaction is sustained by fast neutrons only. Such a reactor must be fuelled with very pure fissile material, such as uranium 235 or plutonium 239. Between the extremes of thermal and fast reactors there is a transition class of so-called 'intermediate reactors' in which both fast and slow neutrons contribute to the fission process.

In general, thermal reactors using natural uranium tend to be rather large, with core sizes of the order of a 10 ft cube. The core size decreases as the proportion of fissile fuel increases, until in a fast reactor the core may not be much larger than a 1 ft cube.

The fission chain reaction is controlled by altering the ratio of neutrons producing fission in the core to those suffering non-productive capture or escaping outside. The reaction can be initiated by withdrawing neutron-absorbing materials such as cadmium or boron from the core, by inserting additional fuel into the core, or by suitably positioning a neutron reflector outside the core, to diminish the proportion of neutrons escaping. The withdrawal of absorbers is the system most frequently adopted, and this method of control is assumed in the following Sections of the paper.

The control members[22] are generally divided into three groups each having a specific function to fulfil. These groups are designated 'safety rods', 'shut-off rods' and 'regulating rods', but it should be emphasized that this subdivision is by no means rigid and in certain reactors the design engineers may consider it desirable to add other groups or even to combine existing groups. The safety rods are intended to be held right out of the core when the reactor is normally shut down and maintenance or fuel loading is in progress. Their function is to provide a margin of extra shut-down control in the event of some unforeseen incident

This is an 'integrating' paper. Members are invited to submit papers in this category giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

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ccurring during this phase, which could bring the core acci-entally to a critical or super-critical state, i.e. a steady or growing hain reaction.

When it is required to operate the reactor the shut-off rods re first withdrawn from the core at a constant slow rate. riticality is not reached during their withdrawal, and they are eld fully out of the core, ready for quick release to shut down e reactor should the need arise. The regulating rods are then ithdrawn slowly and criticality is reached at some point during eir travel. Further withdrawal causes the fission rate, and in onsequence the nuclear power, to increase, and this will con-nue until the rods are reinserted to the original position of iticality. Moving the rods further into the core causes the ower to decrease, and regaining stability at a new operating vel requires the withdrawal of the rods to the starting position. hus the regulating-rod position* corresponding to a steady perating power is not a unique function of the absolute power vel.[23] Since the regulating rods are used to effect fine control reactor power, it is desirable that they should be driven by a rvo motor system which allows variable-speed operation in ther direction.

Nuclear reactors fall broadly into two categories, namely perimental and power. Experimental reactors are required for ndamental nuclear studies over a wide range of operating owers and again at the higher powers for investigations into eutron-irradiation effects on structural and fuel materials. To is end the provision of adequate experimental facilities is the ost important aspect in the design of such a reactor. Power actors, on the other hand, are designed primarily to supply eat which can be efficiently put to use for the generation of ectric power in a land-based station or the production of motive ower in a propulsion unit. The heat removal from the reacting re in either case requires some circulating cooling medium ch as air, carbon dioxide, water, liquid sodium, etc., to trans-ort the heat to a heat exchanger. Whereas in experimental actors this heat removal is secondary to the main function of oviding adequate experimental facilities, in a power reactor is the principal problem, particularly its conversion to useful ork in the most economical and efficient way.

So far as instrumentation is concerned, there are few differences principle between the two categories of reactor, although fferences in detail do arise, and the instrumentation described the paper is based on experimental reactors.

(2) REACTOR KINETICS

In a nuclear-fission chain reaction, neutrons which at some stant of time are causing nuclei of the fuel to divide or undergo ssion, have themselves been produced in an identical process me time earlier. If $K_{eff} = 1$ the neutron density is constant d the reactor is said to be critical. If $K_{eff} > 1$ the neutron ensity is increasing and the reactor is said to be divergent or per-critical. Conversely, if $K_{eff} < 1$ the neutron density is ecreasing and the reactor is convergent or sub-critical. In uational form this behaviour can be written

$$\frac{dn}{dt} = \frac{K_{eff}n - n}{\tau} + S \quad . \quad . \quad . \quad . \quad . \quad (1)$$

he reactivity of the process, ρ, is defined as $(K_{eff} - 1)/K_{eff}$. or small values of ρ this is approximately $K_{eff} - 1$.

Thus
$$\frac{dn}{dt} = \frac{\rho n}{\tau} + S \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

* The regulating-rod position for criticality is a function of various longer-term ects, such as the temperature coefficient of reactivity of the core, the build-up of ion-product poisons within the fuel and the burn-up or depletion of the fuel itself. ese effects are not discussed in detail in the paper, but they are mentioned subse-ently when they have a bearing on the instrumentation of the reactor.

In eqn. (2), if $\rho = 0$ then $dn/dt = S$. The reactor is critical and no multiplication of the fission neutrons is taking place, but the neutron density is slowly increasing linearly at a rate S. This means that, for steady operation, K_{eff} must be less than unity, but for all normal operating levels the neutron density increase due to S is so minute that it can be neglected.

If ρ is not zero, integration of eqn. (2) gives a solution of the form

$$n = \left(N + \frac{S\tau}{\rho}\right)\varepsilon^{\frac{\rho}{\tau}t} - \frac{S\tau}{\rho} \quad . \quad . \quad . \quad . \quad (3)$$

From eqn. (3) if $K_{eff} < 1$, i.e. the reactor is sub-critical, n in time settles down to a value $-s\tau/\rho$. In this region the reactor is functioning as a multiplier of the spontaneous neutrons, the multiplication factor being proportional to $1/\rho$. Subsequent step increase in K_{eff}, but still within the sub-critical region, results in a new equilibrium neutron density which is approached expo-nentially with a time-constant also proportional to $1/\rho$. Thus the time to settle down to the equilibrium value progressively increases with the closeness to critical until, when criticality is reached, the neutron density continues increasing at a rate S as deduced from eqn. (2).

If the reactor is super-critical, i.e. $K_{eff} > 1$, in time the spon-taneous neutron contribution becomes insignificant compared with N and eqn. (3) can be simplified to

$$n = N\varepsilon^{\frac{\rho}{\tau}t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

which shows that the neutron density increases exponentially with time for positive values of reactivity.

Eqns. (1)–(4) are based on the assumption that the neutrons born in fission are all released instantaneously. In a practical system this is not so. In a reactor fuelled with uranium 235 as the fissile material a fraction, $\beta = 0{\cdot}0076$, of the neutrons are delayed, since they originate from the radioactive decay of fission products. Six groups of delayed neutrons have been identified with decay time-constants of 0·07, 0·62, 2·19, 6·51, 31·8 and 80·2 sec respectively. Taking these delayed neutron emitters into account modifies eqn. (1) to

$$\frac{dn}{dt} = \frac{K_{eff}n - \beta n - n}{\tau} + \sum_{1}^{6} \lambda_i r_i + S \quad . \quad . \quad . \quad (5)$$

The production and decay of the delayed neutron emitters in each group is defined by

$$\frac{dr_i}{dt} = \frac{K_{eff}C_i n}{\tau} - \lambda_i r_i \quad . \quad . \quad . \quad . \quad . \quad (6)$$

A complete solution of the simultaneous equations (5) and (6) in response to a step change in K_{eff} leads to an expression for n which is the sum of seven exponential terms

$$n = N\sum_{s=0}^{s=6} A_s \varepsilon^{\mu_s t} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The first term in this series represents the behaviour of the neutron density after the transient terms 1–6 inclusive have died away. These transient terms have decay time-constants very nearly equal to those of the delayed-neutron groups, and thus in theory do not disappear until considerably more than 80 sec have elapsed. In practice, however, the contributions due to the longer-decay groups are small and the transient phase can be assumed to be complete in a few seconds.

A simplified physical approach is to regard the critical reactor at time $t = 0$ as a prompt-neutron assembly with a negative reactivity equal to β. A sudden increase in reactivity by an amount ρ not exceeding β causes the flux density to rise

exponentially in a fraction of a second to a new equilibrium value in accordance with the sub-critical behaviour deduced from eqn. (3) for a system containing no delayed neutrons. Before this phase is complete, however, the effect of the delayed neutrons appears and the flux density then continues to rise exponentially at a much slower rate. The delayed neutrons, in effect, decrease the resulting rate of rise of neutron density, compared with a system having no delayed neutrons, and consequently make the reactor easier to control. The prompt-neutron density increase is given by

$$\left(\frac{N\beta}{\beta + \rho} - N\right) = \frac{-N\rho}{\beta + \rho}$$

For suddenly applied negative reactivity the prompt decrease is calculated as above, but here ρ is not limited to numerical values less than β. After the prompt decrease has occurred, however, the neutron density can never decay faster than the decay time of the longest-delayed neutron emitter present. Thus very large values of negative reactivity are ineffectual in causing a rapid fall in operating level.

If the transients occurring during the first few seconds after the application of a small reactivity step are neglected, an approximate expression for the rise or decay of neutron density is

$$n = NA_0\varepsilon^{\mu_0 t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where μ_0 is a function of ρ. The relationship between μ_0 and ρ is shown in Fig. 1. In a thermal reactor the mean neutron lifetime is approximately 10^{-3} sec; Fig. 1 therefore shows that μ_0 is very much smaller than ρ/τ, thereby confirming that the growth or decay of neutron density in eqn. (8) is much slower than that in eqn. (4) for a given value of ρ. It must be remembered, however, that eqn. (8) is applicable only for positive values of ρ not exceeding β. Should ρ ever become greater than the fraction of delayed neutrons present, the reactor would become super-critical on prompt neutrons alone and a very rapid growth of neutron density would result—a condition which must be avoided at all costs. The quantity $1/\mu_0$ is known as the reactor period and corresponds to the time taken by the neutron density to increase by a factor ε. The time taken to increase by a factor 2 is known as the doubling time and is equal to $0 \cdot 693/\mu_0$.

For each fission which occurs in the fuel, thermal energy equivalent to 180 MeV is released. Nuclear power is thus proportional to the fission rate in the core, and this in turn is a function of the product of neutron density and neutron velocity. The product of neutron density and neutron velocity is usually referred to as the neutron flux and is measured in units of neutrons per centimetre squared per second. In a given system, however, the neutron velocity, or velocity distribution, can be assumed to be constant, so that direct proportionality exists between nuclear power, neutron density and neutron flux.

(3) INSTRUMENTATION REQUIREMENTS

The instrumentation of a nuclear reactor can be subdivided conveniently under three headings, namely measurement, control

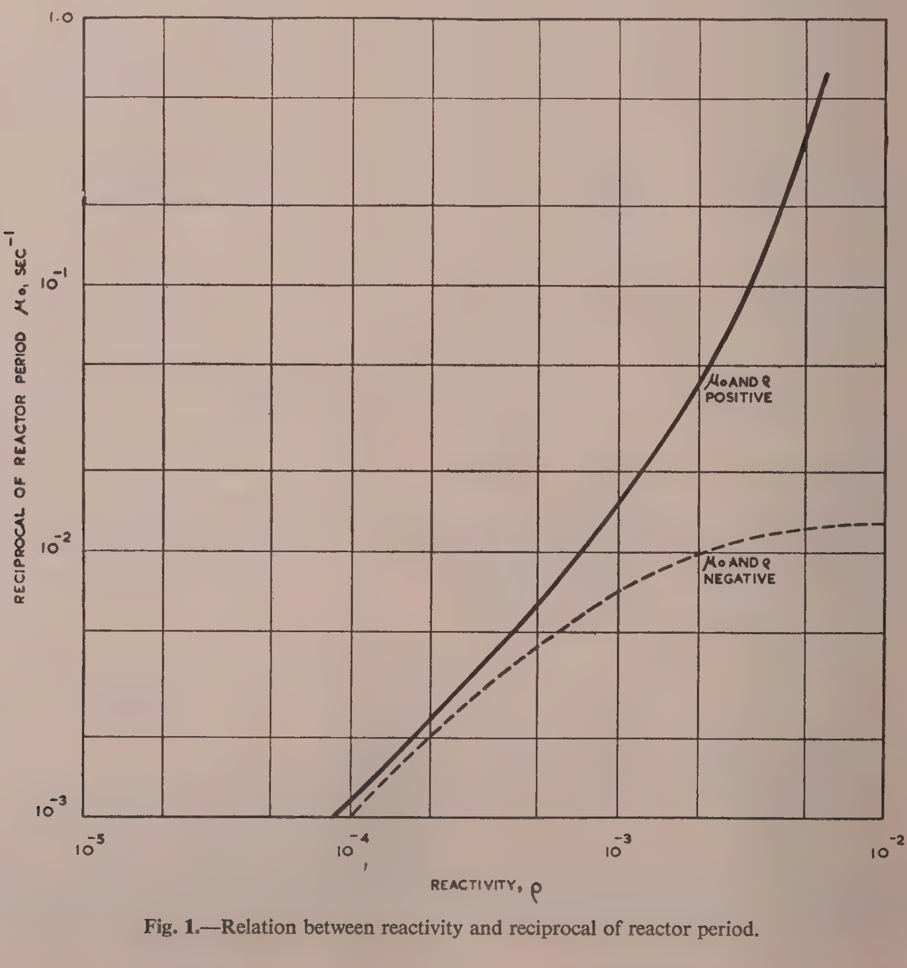

Fig. 1.—Relation between reactivity and reciprocal of reactor period.

nd safety. Many and varied measurements are required, but ndoubtedly the most important are those which indicate the bsolute power level of the reactor and the rate at which this vel is changing. The operating range from shut-down to full ower varies with the type of reactor and the duration of the ut-down, but is rarely less than four decades. With a heavy-ater-moderated reactor, for instance, which has been in opera-on for some time and then shut down, the neutron flux takes everal days to fall to 10^{-6} of its operating value. This apparently igh shut-down level after such a long time is due to additional elayed-neutron emitters which are produced in the heavy water y the γ-active fission products of the fuel, some of these so-called hoto-neutron' groups having decay periods of several days. heir proportion is very small—not enough to affect the opera-on significantly at normal levels—but sufficient to take control everal decades below this, following a shut-down. With a eactor of this type, then, power-level instrumentation over six ecades is desirable. With a graphite-moderated reactor, on the ther hand, the shut-down neutron flux may fall to 10^{-10} of the itial operating value, thus demanding instrumentation of con-iderably wider range. The importance of being able to measure e neutron flux and its rate of change under shut-down con-itions is apparent from the exponential nature of its increase r positive values of reactivity. This, together with the danger f reaching prompt criticality, emphasizes the extreme hazard f withdrawing control members without being able to observe strumentally the behaviour of the reacting core. This wide ange of power-level instrumentation can be realized only by easuring the neutron flux itself in or near to the core, and thus eutron-flux measurements form a very important part of the strumentation of all reactors. Such measurements are doubly nportant, because they provide a nearly instantaneous indica-on of the behaviour of the chain reaction within the core and re thus well suited for the operation of level and period safety evices which should act very quickly.

Although neutron-flux measurements are possible over a very ide range, difficulties (due mainly to the fact that neutron etectors are also slightly γ-sensitive) arise when the range to be overed exceeds some 6–7 decades. For this reason it is cus-omary to place in the reactor core neutron sources which con-ibute to the rate term S in eqn. (2), thereby raising the shut-down vel and reducing the instrumentation range. By this expedient, e instrumentation range of a graphite-moderated reactor can be educed to seven decades for only a very small resulting loss in eactivity.

At operating levels it is also desirable to measure the reactor ower in terms of the heat output of the core, i.e. thermal power, ecause the radioactive decay of fission products which build up the fuel may in time contribute a small proportion of thermal nergy to that released in the fission process. More important, owever, is that, after shut-down, the heat contribution of the fission products, which decay very slowly, will ultimately exceed that due to the fission reaction itself. Thus the flow of coolant through the core must be adequate to deal with this component, although the indicated nuclear power from neutron instrumentation might be very much less.

There are many other nuclear and physical measurements necessary for the efficient and safe operation of the plant. Radiation levels in working areas require monitoring for health purposes; numerous activity checks must be carried out on the coolant and other parts of the system, and these are augmented by a considerable proportion of physical measurements of temperature, pressure, flow, etc.

The control of the reactor is based on information provided by the measuring instruments. This information may be interpreted by the reactor operator and the appropriate movements of control members effected manually, or the measured data can be used to initiate automatic control action. During starting-up, the most vital measurements are those of nuclear power and reactor period. When approaching and running at full power, temperature effects, coolant flow conditions and thermal power become very important. For short-term variations, control must still be based on nuclear power, but it is more than likely that the long-term control of the reactor will be dictated by thermal-power considerations. After shut-down, both nuclear and thermal-power instruments have important and varied roles to play, as discussed earlier. The control instrumentation is mainly concerned with the motorization of the control elements, particularly the regulating rods, which require variable-speed reversible operation. The facility of automatic control necessitates additional instruments to compare measured with demanded values and to provide an error-signal output to the regulating-rod drive system.

The safety of a nuclear reactor is a subject of vital importance, and a considerable part of the instrumentation is necessary to ensure that no error of judgment on the operator's part, or the occurrence of a fault in some component, can bring about a situation which might result in the reactor getting out of control and damaging itself. Many of the safety circuits derive their information from the measuring instruments, but there are others which require their own special detectors. Collectively one may group under the heading of safety instrumentation those detectors, instruments and subsequent circuits which give visible and audible warning of the occurrence of fault conditions, and may even shut the reactor down automatically should the fault be considered sufficiently serious. Much of this section of reactor instrumentation consists of relay circuits designed in accordance with a basic code or philosophy of reactor safety.

A family tree of reactor instrumentation is shown in Fig. 2. In addition to the three main headings of measurement, control and safety, each has been further subdivided and the detailed items will now be discussed in the following Sections of the paper.

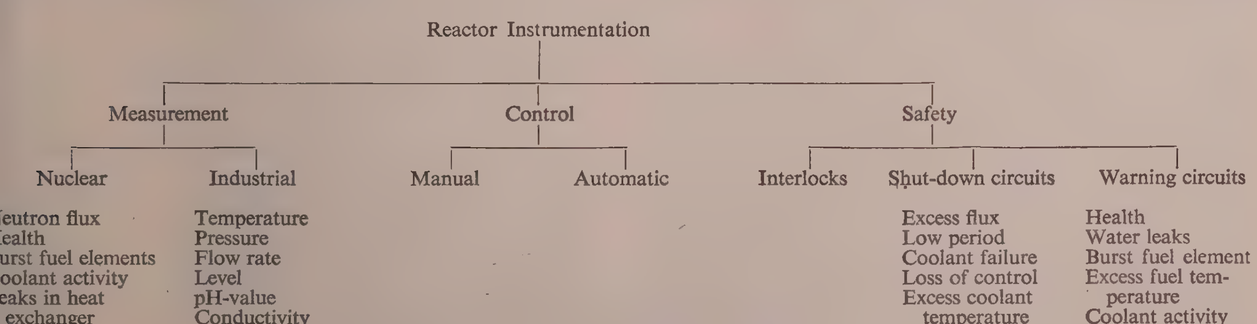

Fig. 2.—Family tree of reactor instrumentation.

It must be emphasized, however, that this analysis is a general one, and that for a particular reactor some items may not be applicable and others may require addition.

(4) MEASUREMENT

(4.1) Nuclear Measuring Instruments

(4.1.1) Neutron Flux.

The simplest method of measuring the slow-neutron flux level at some point adjacent to the reactor core is to use a mean-current ionization chamber in conjunction with a d.c. amplifier. The mechanical design and electrical characteristics of the type RC/1 ionization chamber, shown in Fig. 3, have been described in the literature,[4, 24] so only those characteristics which affect the subsequent measuring instruments and are relevant to the reactor control are included here. The ionization chamber may be filled with boron trifluoride gas or the electrodes may be coated with solid boron and the chamber filled with an inert gas such as argon, methane or hydrogen. In either case the neutrons react with the boron 10 nuclei, producing high-speed α-particles and charged lithium nuclei which cause ionization of the gas, resulting in a collected current which is proportional to the magnitude of the neutron flux at the ionization chamber. By varying the gas pressure and/or the coated area, the chamber sensitivity may be adjusted within limits to give a compromise between the neutron flux to be measured and the current range best suited to the measuring instruments. Currents to be measured generally lie within the range 10^{-12}–10^{-4} amp, the larger current corresponding to a neutron flux in the region of 10^{10} n/cm^2/sec. As was mentioned earlier, such ionization chambers are also sensitive to β- and γ-radiation, the mean current due to γ-radiation of intensity 1 r/h being approximately equal to that due to a slow-neutron flux of 10^2 n/cm^2/sec. This γ-sensitivity acts to limit the useful range of the ionization chamber itself in two ways: the materials of the ionization chamber become β- and γ-active, owing to continuous neutron irradiation, and this activity sets up a background current which, on removal of the neutron flux, decays at a rate which depends on the activities present. For a typical RC/1 chamber the principal activities have decay half-lives of $2 \cdot 3$ min (aluminium electrodes) and $2 \cdot 5$ h (manganese impurities) and the background current, which is approximately 5×10^{-4} of the neutron current at the instant of removing the neutron flux, falls to $6 \cdot 5 \times 10^{-7}$ in 30 min and to $2 \cdot 0 \times 10^{-7}$ in some 8 h. This ionization chamber is suitable for the control of a heavy-water-moderated reactor after shut-down, owing to the long-lived photo-neutron groups which retard the neutron-flux decay. It is not, however, suitable for control of a graphite-moderated reactor after shut-down, since the neutron flux never decays with a half-life longer than 55 sec ($80 \cdot 2 \times 0 \cdot 693$). Some improvement can be gained with the RC/1 chamber by using boron highly enriched in the boron 10 isotope and by judicious choice of filling gas and pressure. This improves the neutron sensitivity over the γ-sensitivity by about 10, and consequently reduces the above residual-current figures by the same amount. Even so, the residual current will still exceed the neutron current at some period during the first 30 min or so after shut-down. This can be further improved by constructing the chamber of very pure magnesium or magnesium–zirconium alloy, both of which have considerably lower short-lived residual activity than aluminium. Other methods of overcoming this problem make use of extra equipment. A second ionization chamber, which has been screened from the neutron flux at full-power operation of the reactor, and therefore not activated, can be moved into the measuring position at shut-down and can take over control. Alternatively, a compensated ionization chamber having a second compartment sensitive only to γ-radiation may be used; the currents from the two halves are subtracted, and if the γ-sensitivities are initially adjusted to equality, considerable long-term γ-cancellation can be achieved. Finally, a pulse-counting neutron detector with associated equipment will provide a substantial improvement since the neutron pulses are appreciably larger than those due to β- and γ-radiation and may be separated by amplitude discrimination. The moving-ionization-chamber and pulse counting methods have been used in a number of reactors. Compensated chambers and chambers constructed of magnesium or magnesium–zirconium have not yet come into general use in Britain, but their design is under active study.

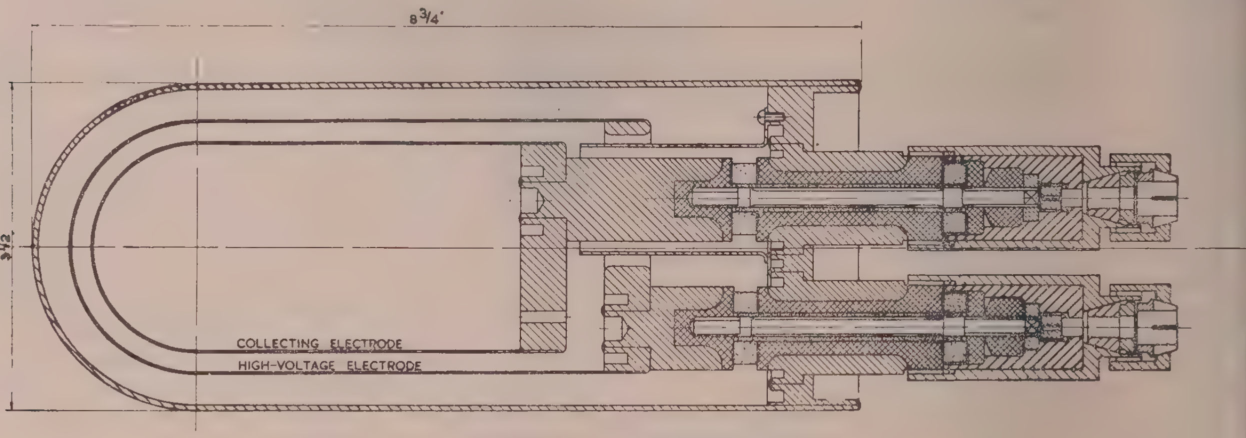

Fig. 3.—Type RC/1 ionization chamber.

In addition to residual activities in the ionization chamber itself, the operating range can also be limited by external γ-activity, either from the active fission products in the reactor fuel or from adjacent structural materials which have themselves become active through neutron irradiation. This can be minimized in part by surrounding the ionization chamber with chemical lead, which attenuates γ-radiation much more than the neutron flux. It is customary in Britain to surround the wide range chambers with lead some 4 in thick, which reduces the γ-ray intensity by a factor of 300 and the neutron intensity by a factor of $1 \cdot 6$. However, as was mentioned earlier, γ-radiation of 1 r/h sets up a background current equivalent to approx

ately 100 n/cm²/sec, and these figures are fundamental to the C/1 type of chamber. A flux of 100 n/cm²/sec gives a current f about 10^{-12} amp, and this may be regarded as a lower limit to e current which can be measured easily and quickly. Thus -radiation of 1 r/h is the maximum intensity in which the RC/1 nization chamber can satisfactorily measure low neutron fluxes.

A compensated chamber should allow this to be raised by a ctor of some 10–20. Where higher γ-ray intensities are met, ulse-counting detectors offer the only solution at present.

The pulse-counting neutron detectors used in reactor instru-entation are the boron trifluoride proportional counter and the ssion counter (Figs. 4 and 5). The former detects neutrons as aggravates the γ-ray background difficulty. Fission counters offer the best solution here.

For the measurement and indication of the mean current from the RC/1 ionization chamber, three types of d.c. amplifier are customarily used. The first—known as the 'multi-range linear'—is a simple electrometer-valve amplifier,[5] in which the ionization-chamber current develops a voltage across a measuring resistor connected between the amplifier input and output terminals. A block schematic of such an arrangement is shown in Fig. 6. The output voltage of the amplifier is equal to that developed across the measuring resistor, and the wide range of ionization-chamber current is accommodated by switching this resistor,

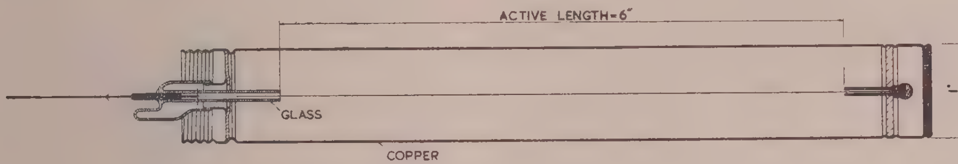

Fig. 4.—Boron-trifluoride proportional counter.

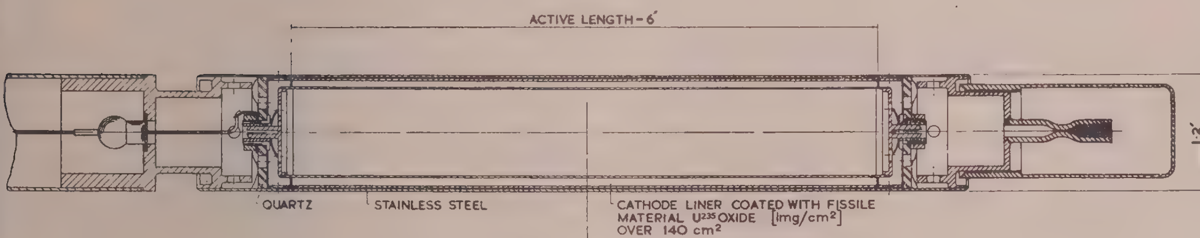

Fig. 5.—Fission counter.

efore, by the (B^{10}, n) reaction, and for a counter of the size shown, lled with enriched boron trifluoride to 40 cm Hg, the slow-eutron sensitivity is about 3·5 counts/sec for a flux of n/cm²/sec; this type of counter will work satisfactorily in a -flux of some 200–300 r/h, and the maximum counting rate is the region of 5×10^4 counts/sec. The fission counter detects eutrons by the (U^{235}, n) reaction, the resulting fission fragments ausing ionization of the filling gas. The neutron-induced fission ulses, relative to the γ-pulses in this type of counter, are much rger than in the proportional counter; they are also much horter in duration, and these two effects enable the fission ounter to operate satisfactorily in γ-fluxes up to 10^5 r/h. The ensitivity of the counter shown is approximately 0·05 counts/sec r a flux of 1 n/cm²/sec, and counting rates up to 5×10^5 ounts/sec are possible. Because of their higher sensitivity, oron trifluoride proportional counters are frequently used for xperimental measurements during the initial approach to itical conditions of a new reactor. A pulse-counting system stalled as part of the control instrumentation might also use a roportional counter on, say, a zero-energy experimental reactor, ut on higher-power reactors the tendency is to use fission ounters.

What has been said so far about neutron detectors is relevant slow or thermal neutrons. In the great majority of cases what required is the measurement of slow-neutron flux, because ven in a fast reactor of moderate size the core is surrounded y some moderating material which thermalizes the neutrons scaping outside and reaching the detectors. The problem of easuring fast-neutron flux has arisen on small zero-energy fast eactors. All the detectors so far mentioned are much less ensitive to fast neutrons than to thermal neutrons, and this usually in decade steps. To minimize zero drift of the amplifier a full-scale output voltage of 10 volts is used. This necessitates measuring resistors ranging from 10^5 to 10^{12} ohms—values which do not lead to serious practical difficulties (10^{-12} amp corresponding to one-tenth full-scale deflection on the most sensitive

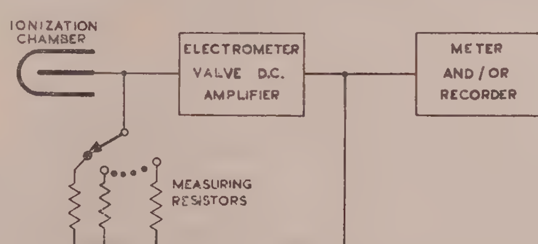

Fig. 6.—Multi-range linear channel.

range). On the higher current ranges wire-wound resistors can be used and an overall accuracy of better than 1% maintained. On the lower current ranges high-value composition resistors are required and a deterioration in accuracy must be accepted. The merit of such a measuring channel is its simplicity and reliability.

The second type of d.c. amplifier is one whose output voltage varies as the logarithm of the input current. The advantage of an amplifier having such a characteristic is apparent when it is remembered that a positive step in reactivity ultimately causes the neutron density, and in consequence the ionization-chamber current, to increase exponentially as $\varepsilon^{\mu_0 t}$. This form of input to a logarithmic amplifier gives an output voltage increasing linearly

as $\mu_0 t$, and if this output is subsequently differentiated, a voltage proportional to μ_0 or inversely proportional to reactor period is obtained. Thus a logarithmic amplifier with differentiator provides a measurement of reactor period over a wide range of power levels.

The logarithmic characteristic is generally obtained from some thermionic element such as a diode. The relationship between diode current and voltage when used in the retarding field region is given by:

$$I = I_0 \varepsilon^{eV/kT} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

At the low-current end eqn. (9) is limited by reverse current in the diode, and at the high-current end by a transition to Child's law. Between these limits, however, it is usually possible to achieve a current range of about six decades over which eqn. (9) is valid. If a diode operating under retarding field conditions is therefore used in place of the measuring resistor in an electrometer-valve type of d.c. amplifier, the output voltage will vary as the logarithm of the input current over a wide range. The principal disadvantage of such a simple system can be appreciated if eqn. (9) is rewritten in the form

$$V = \frac{kT}{e}\log_\varepsilon I - \frac{kT}{e}\log_\varepsilon I_0 \quad . \quad . \quad . \quad . \quad (10)$$

This shows that a change in the diode heater voltage will alter the slope of the $V/\log_\varepsilon I$ characteristic (i.e. voltage per decade) and also cause the whole characteristic to move bodily (i.e. voltage for a fixed current). The latter is the more serious effect, since it is controlled by the term $(kT/e)\log_\varepsilon I_0$ in eqn. (10) and I_0 is a rapidly varying function of heater voltage. This can be minimized by a factor of about 10 by using a second similar diode[6] to balance the change in I_0 with heater voltage. Even so, for satisfactory operation, some degree of heater stabilization is desirable.

An alternative method[7] of stabilization uses a pentode operating under conditions of constant anode current, as shown in Fig. 7.

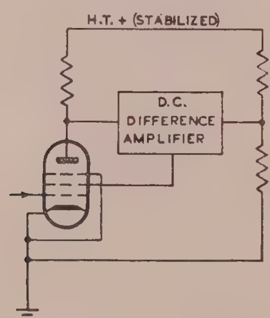

Fig. 7.—Pentode stabilization of logarithmic characteristic.

The anode potential, and consequently the anode current, is prevented from altering by the d.c. difference amplifier, which feeds a voltage back to the screen to counteract any change in grid voltage caused by variation in ionization-chamber current. If the amplification factor, G, of the valve is constant, the screen potential will vary as the logarithm of the input current with a voltage change per current decade of G times that on the grid. The grid-voltage change per decade is the same as for a diode and averages about 0·2 volt. The relevant stabilization of this circuit can be understood by considering the effect of an increase in heater voltage. The ionization-chamber current does not alter, and therefore the grid potential must move negative to satisfy the grid-cathode diode relationship. The increased emission will tend to increase the anode current, but this is counteracted by the negative change in grid potential. If this balance were perfect neither the anode current nor the screen potential would alter. As before, however, for really satisfactory results, some degree of heater stabilization is desirable.

This type of logarithmic d.c. amplifier followed by a differentiator has been used on a number of reactors in Britain. With an ME1400 as input valve and an anode current of 200 μA the logarithmic grid-current range extends from 5×10^{-11} to 5×10^{-5} amp. Alternatively, an ME1403 with an anode current of 10 μA covers a range from 10^{-13} to 10^{-7} amp. Amplifiers using the ME1400 with simple heater stabilization have exhibited long-term drifts considerably less than 10% of full-scale deflection.

The output of the differentiator is usually fed to a meter scaled inversely in reactor period or doubling time, the doubling-time scale in common usage ranging from -20 sec through ∞ to $+5$ sec.

The third type of d.c. amplifier for ionization-chamber-current measurement is also a linear one, in which the output voltage is compared with a reference voltage and the difference, which is a measure of the error between reactor power and demanded power, is displayed on a centre-zero meter. The demanded power-level may be varied by changing the reference voltage, or the reference voltage may be held fixed and the d.c.-amplifier measuring resistor changed. Both methods have been used, the former giving an absolute and the latter a percentage power-error signal. This measuring channel is used either manually or automatically to regulate the reactor power, and consequently should be very accurate and stable. The demanded power-coverage required from such a channel does not usually extend more than two or three decades below full-power operation. The use of this error signal amplifier for automatic power regulation also necessitates that its response time should be as short as possible. This requirement for high bandwidth, together with high accuracy and stability, leads to the choice of wire-wound measuring resistors and a low drift d.c. amplifier of the electrometer-valve type with contact-modulator[5] zero stabilization.

A block schematic of such a 'backed-off' measuring channel is shown in Fig. 8. The long-term drift of the d.c. amplifier is kept

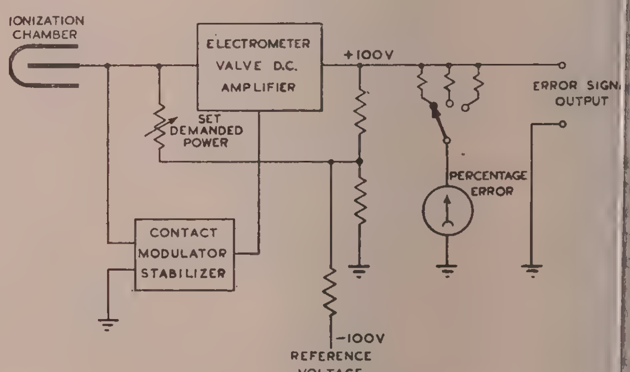

Fig. 8.—Backed-off channel.

below 50 μV by the contact-modulator stabilizing section. Thus for a specified accuracy and stability of 0·1%, it is in order to work with a full-scale voltage of 100 mV across the measuring resistors, and this places the latter comfortably within the wire-wound range. To ensure a useful output voltage from the d.c. amplifier, the feedback to the measuring resistor is derived from a voltage divider having a ratio of 1 000 : 1. Thus an output voltage of 100 volts appears at the amplifier output terminal

r a power-error signal of 100%. The error meter has three nsitivity ranges, corresponding to full-scale errors of 1–0–1%, –0–10% and 100–0–100%.

The three types of nuclear-power measuring channels described e complementary. They have their individual functions to lfil and are used with separate ionization chambers on most ritish reactors. It is customary to record the power-level formation provided by the multi-range linear and logarithmic c. amplifiers.

Pulse-counting neutron detectors require more complex easuring instruments than mean-current ionization chambers. he same instruments, however, are suitable for use with both oron-trifluoride proportional counters and fission counters and omprise a nuclear pulse amplifier, a pulse-amplitude disiminator and a pulse ratemeter. The pulse amplifier is conentional and consists of a head amplifier mounted integral with, near to, the counter and a main amplifier located in the control oom. A maximum gain of about 3×10^5 is required, and for ounting rates up to 5×10^5 counts/sec, the bandwidth should ot be less than 2 Mc/s.[8] The amplitude discriminator should so be capable of satisfactory operation at these high counting tes,[9] and for reactor-control applications it is convenient to se a logarithmic[10] ratemeter scaled from 1 to 10^6 counts/sec, nce this allows the addition of a differentiator to provide period formation.

All the neutron detectors described require the application of polarizing voltage to collect the ionization. This does not sually exceed 500 volts for mean-current ionization chambers nd fission counters, and since the voltage is not critical but eed only be large enough to saturate the detector fully, batteries ave proved very satisfactory for this purpose. For the boronifluoride proportional counter, however, a voltage between and 2 kV is needed, and since it is convenient to be able to vary is, the tendency has been to use mains-driven high-voltage applies with these counters.

.1.2) **Health.**

On research reactors in particular, where holes in the shielding n be opened to allow beams of radiation to be brought out for perimental purposes, the judicious positioning of installed area ealth monitors is most important. Portable monitors and rsonnel protection devices such as pocket electroscopes and m badges are also very necessary, but since these are reasonably andard, and have already been described in the literature,[11] ly the installed health instrumentation is discussed here.

The radiations requiring continuous monitoring in working eas around a research reactor are γ-rays and slow and fast eutrons. γ-ray monitors invariably comprise a mean-current nization chamber feeding a d.c. amplifier. Instruments in esent use have a T.P.A. type [12] of ionization chamber filled with gon to 2 atm and a logarithmic d.c. amplifier to measure the nization-chamber current; the range of γ-ray dose rate covered from 1 to 10^5 mr/h (the tolerance dose rate is approximately mr/h). The merit of logarithmic scaling is that low radiation vels below and around a tolerance can be measured reasonably curately, and yet the instrument will remain on scale should a gh level of radiation occur. The T.P.A. ionization chamber has steel case and aluminium electrodes, and thus γ-ray measureent becomes inaccurate below energies of about 300 keV, owing wall effects. In a reactor area this is not very important, since gh-energy γ-rays are predominant, but an air-wall type of nization chamber allowing the correct contributions from the w-energy γ-rays to be collected is at present under design and ill ultimately replace the T.P.A. chamber on this instrument. here are two units, the ionization chamber with attached head nplifier sited in the working area, and a main amplifier with indicator in the control room. The head amplifier also carries a slave meter showing the radiation level indicated in the control room, and a red warning light which is illuminated when the radiation dose rate exceeds 10 mr/h. A dozen or more γ-ray monitors of this type may be in use on a large experimental reactor installation, and it is also customary to make a continuous recording of their outputs on a multi-point strip-chart recorder.

The same instrument can be used for slow-neutron health monitoring by replacing the γ-sensitive ionization chamber by one filled with boron trifluoride to the appropriate pressure. However, for area monitoring it is unlikely that a slow-neutron flux would exist without being accompanied by γ-radiation of at least equal or greater biological effect. Thus installed slow-neutron monitors are rarely used. Intense slow-neutron beams may exist, but these are localized, and monitoring is usually carried out with portable instruments.

A given flux of fast neutrons is some 20–30 times more damaging biologically than the same flux of slow neutrons. Fast neutrons are also easily scattered over a wide area, so installed fast-neutron monitoring is of equal importance to γ-ray monitoring. Fast neutrons are difficult to measure because of the low tolerance level and the fact that they are usually accompanied by some γ-ray and slow-neutron radiation. Pulse counting offers the best method of discriminating against γ-ray background, but the pulse counter must be of a type insensitive to slow neutrons, so that fission counters are not suitable. The proton recoil counter satisfies these requirements, and a counter of this type, with characteristics adjusted to make the counting rate also dependent on the energy of the incident fast neutrons, has been described in the literature.[13, 14] A number of these counters have been constructed at Harwell and used for fast-neutron monitoring in conjunction with a simplified amplifier, discriminator and ratemeter. The principal disadvantage is the very low counting rate of 0·5 count/sec, corresponding to a tolerance level of fast neutrons. An increase in sensitivity by a factor of about 10 would simplify the problem very considerably, and this is under active study.

Two other types of standard health monitor are frequently installed in reactor buildings. The first is the 'hand and foot' monitor[15, 16] for checking the contamination on the hands and feet of personnel in the building, and the second is a dust monitor[17] for checking the level of active dust in the air.

(4.1.3) **Ancillary Activities.**

There are numerous other activities, associated primarily with the coolant, in the higher-power reactors which require measurement. In general, most of these measurements can be made using standard nuclear-laboratory types of instrument, but some difficulty may be experienced in the first place in obtaining and isolating the requisite activity in a form suitable for presentation to the detectors.

An instance of this occurs in the detection of ruptured fuel-element sheaths. Such ruptures must be discovered as early as possible, otherwise fission products will ultimately cause serious contamination of the coolant. The method which has been adopted at Harwell is to monitor the coolant for the presence of β-active fission products. Since the coolant is likely to contain many other induced activities, the fission-product activities must first be isolated. The escaping fission products contain gaseous isotopes of xenon and krypton, and in a gas-cooled reactor these can be isolated by filtering the coolant. In a water-cooled reactor a stream of helium is passed over the water surface and the gaseous fission products diffuse into the helium. Subsequently, in both cases the gas is allowed into a precipitation chamber containing a moving wire at a high potential. Some of the xenon

and krypton decay products are solid and are collected on the wire and then presented to a β-counter for measurement. Such a 'burst slug' detection system has been fitted to a number of British reactors. There are many practical problems associated with obtaining the earliest possible warning and then locating the offending fuel element, at the same time keeping the amount of equipment used within economic limits. This is particularly so in a gas-cooled graphite-moderated reactor, which may contain a very large number of individual fuel-element channels. Here it is customary to divide the channels into groups with continuous monitoring on each group. The isolation of a rupture occurring within any particular group can then be effected by a scanning process.

(4.2) Physical Measuring Instruments

In small zero-energy experimental reactors the physical instrumentation required is usually very small compared with the nuclear instrumentation just described. This may involve a few temperature measurements, and, in a fluid-moderated reactor, perhaps one or two pressures and fluid levels.

In a reactor generating considerable thermal power and necessitating a circulating coolant and heat exchanger the converse is the case, and the physical instrumentation soon swamps everything else. One of the most important physical measurements is that of thermal power obtained from the coolant flow and inlet and outlet coolant temperatures. There are many others associated with temperatures and pressures throughout the system, fluid flow rates and levels, pH-values, conductivity, leaks, etc. It is not proposed to go into detail on the physical measuring instrumentation in the paper, both because of shortage of space and the fact that such instrumentation is well known and in the main conforms to standard industrial practice. It does, however, constitute a vital part of the complete instrumentation of a nuclear reactor, and is intimately linked with the safety circuits to be described later.

(5) CONTROL

(5.1) Manual

The start-up and subsequent power-level control of a nuclear reactor requires the sequential withdrawal of the safety, shut-off and regulating rods. The first two groups are withdrawn from the core at a slow constant speed corresponding to a safe maximum rate of addition of reactivity as laid down by the reactor design engineers. Such control members are driven through reduction gearing by conventional 3-phase induction motors, and their position during travel is indicated in the control room. The rods are coupled to the reduction gearing by magnetic clutches, which must be energized before withdrawal can commence. Subsequently during travel, or at rest in the fully-out position, the rods can be dropped into the reacting core to provide a controlled or emergency shut-down, by interrupting the current supply to the clutch electromagnets. The regulating rods are the last to be withdrawn and have the same indicating and release facilities as the others. As the reactor diverges, however, at some point during the regulating-rod travel these members become responsible for the dynamic control of the reactor, and it is essential that their driving mechanism should be capable of variable-speed operation in either direction. Under conditions of manual control this facility must be available to the operator at the control desk.

The maintenance of a constant power level by the operator is eased if the speed of the regulating-rod drive motor is made proportional to the rotation of a knob on the control desk. This implies the use of a velocity-controlled servo motor, and the two systems which have been most used on British reactors are the Amplidyne[18] and the Velodyne,[19] d.c. motors and generators being employed. Some development work has recently been carried out on the use of a variable-speed 2-phase induction motor to meet this requirement. The induction motor is attractive because of its synchronous speed, which cannot be exceeded, the absence of commutator brushes, which can cause interference to adjacent measuring instruments, and its reliability. A block schematic of a speed-controlled induction motor to be used for the regulating-rod drive on one of the new Harwell research reactors is shown in Fig. 9. The induction motor must

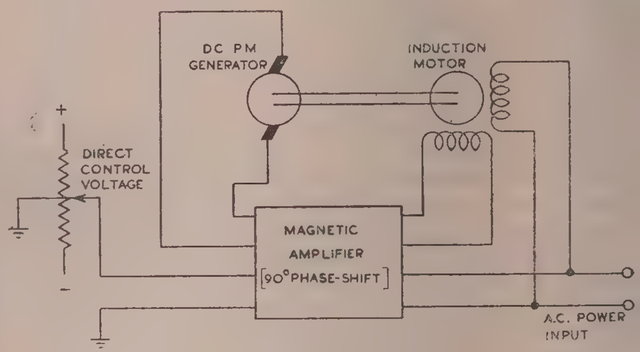

Fig. 9.—Induction-motor speed controller.

have a falling torque/speed characteristic throughout the speed range from zero to synchronism; thus a motor having a rotor resistance equal to or greater than the standstill reactance is required. The speed of the motor is altered basically by varying the power supplied to the quadrature winding of the stator. This is controlled by the magnetic amplifier, which supplies the requisite power to drive the motor at such a speed that the direct voltage from the permanent-magnet generator is approximately equal to the applied direct control voltage. For the system to be reversible the phase of the magnetic-amplifier output must be sensitive to the polarity of the control voltage. At very low speeds the tendency for the induction motor to overheat can be overcome by using a somewhat larger motor and under-running the mains phase. The possibility of supplying both phases from the magnetic amplifier is also under investigation.

(5.2) Automatic

The term 'automatic control' is usually understood to mean the automatic regulation of the reactor power after it has reached the demanded level. The prior phase of raising the power from its shut-down value to the demanded level can also be effected automatically and is usually referred to as 'automatic start-up'. In either case the primary control loop is based on the nuclear-power level and period instruments, but from a longer-term aspect the demanded value of nuclear power may itself be under the control of thermal-power instruments. This is particularly so in electricity-producing and propulsion reactors, where the heat output of the reactor must be kept in step with the load demand. Many formidable problems exist here, and the present line of attack at Harwell is to construct an electrical analogue of the complete plant and to carry out investigations into plant control and stability on this. In the paper, however, the discussion is limited to a consideration of the primary control loop only.

The simplest approach to automatic control is to use the power-error signal from the backed-off flux channel to drive the regulating-rod motor in the right direction to restore equilibrium. For automatic control over a wide range of power level the error-signal amplitude should not be dependent on the absolute power; thus a fractional or percentage error-signal is required.

If, following the application of a small step in reactivity, the initial transients can be neglected, it follows from eqn. (8) that

$$P_t = P_0\varepsilon^{\mu_0 t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

If μ_0 is itself varying with time, eqn. (11) may be rewritten as

$$P_t = P_0\varepsilon^{\int \mu_0 dt}$$
$$= P_0\left(1 + \int \mu_0 dt\right) \quad . \quad . \quad . \quad . \quad (12)$$

for small values of μ_0.

The power error is $P_t - P_0 = P_0\int \mu_0 dt$ and the fractional power error is $\int \mu_0 dt$. The voltage applied to the regulating-rod servo system is thus $A\int \mu_0 dt$, where A is a constant of the power-error measuring instrument. If it is further assumed that μ_0 varies linearly with small displacement of the regulating rods, the equation of motion of the closed loop is

$$\frac{d\mu_0}{dt} = -CA\int \mu_0 dt$$

where C is a constant of the regulating-rod servo system. Thus

$$\frac{d^2\mu_0}{dt^2} + CA\mu_0 = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Eqn. (13) contains no damping term and it follows that this simple automatic control loop must be oscillatory. In the derivation of eqn. (13), however, the theoretical assumptions which have been made imply that both the reactor and the regulating-rod servo system are perfect integrators with a constant 90° phase lag. In the reactor this is not so, as can be seen from the curves[20] in Fig. 10, which show how the amplitude

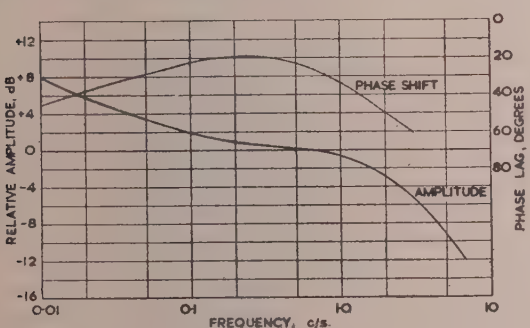

Fig. 10.—Reactor amplitude/frequency and phase-shift/frequency characteristics.

and phase of the resulting nuclear power modulation varies with small sinusoidal changes in reactivity about zero level. There is a region in the vicinity of 0·25 c/s where the reactor phase-lag is only 20°, and it should therefore be possible to design the previous simple control loop to have a non-oscillatory operation. As the reactor phase-lag approaches 90° at frequencies above 1 c/s, and that of a practical regulating-rod servo system will exceed 90° at higher frequencies, the danger of oscillation is still present unless the loop gain is kept sufficiently low. A regulating system of this type has been used on a number of British reactors.

A higher loop gain may be used if an additional error signal component with a leading phase angle is introduced. This is the equivalent of a damping term in eqn. (13) and is derived from the differentiating section of the logarithmic channel. This gives a voltage error-signal equal to $B\mu_0$, where B is a constant of the measuring instrument. This signal is again independent of absolute power level, and when combined with the fractional power error modifies eqn. (13) to

$$\frac{d^2\mu_0}{dt} + CB\frac{d\mu_0}{dt} + CA\mu_0 = 0 \quad . \quad . \quad . \quad (14)$$

Critical damping is realized when

$$CA = \left(\frac{CB}{2}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Eqn. (15) defines the relationship between the constants A, B and C.

Because of additional phase lags in the measuring circuits and the regulating-rod servo system, which become significant at higher frequencies, the overall stability of an automatic control loop of the type described must be subject to a Nyquist plot to ensure that the total loop gain has fallen below unity by the time the phase shift reaches 180°. An additional effect which can assist the stabilization of the control loop to some extent, but only in the region of full-power operation, is the temperature coefficient of reactivity of the fuel. For uranium this is about $-1{\cdot}5 \times 10^{-5}$ per deg C, and at high fuel temperatures it can exert a considerable self-stabilizing action.

An alternative method of automatic control which has been used on some American reactors[21] is based on a discontinuous operation of the regulating-rod servo system. No corrective action is taken until the reactor power error exceeds some specified value above or below the demanded level. The regulating rods are then set in motion at full speed in the right direction to correct the error, and stop as soon as the error again enters the permissible band. This method of control is claimed to have some advantages over the proportional method, particularly on circulating-water-moderated reactors, which tend to superimpose an appreciable noise component on the error signal.

The proportional method of automatic control using power-error and reciprocal-period signals from the measuring instruments is also applicable to the problem of automatic starting-up. At shut-down, the power-error signal is nearly -100%, so the regulating rods are withdrawn until the reciprocal-period signal just balances the power-error signal. The relative values of A and B must be such that this equilibrium state results in an acceptable reactor period, generally in the region of 30 sec. It is unlikely that the constant values required to meet this condition will be the same as required for optimum control at the demanded operating level, so that switching between automatic starting-up and automatic control is necessary after the reactor has been brought up to power.

Throughout most of the six or seven decades of power range the error signal remains very near to -100%, and thus the power level of the reactor is raised automatically with a period equal to the initial equilibrium value. When the power is about a decade or so from the final value, the error signal begins to decrease. This upsets the control-signal balance, causing the regulating rods to move into the core until a new equilibrium is reached, corresponding to a reduced reciprocal period. This process is continuous as the power approaches the demanded level, until finally both the power-error and reciprocal-period signals are reduced to zero.

A simple automatic start-up system of this type has been tested experimentally on Bepo,[7] the larger of the two Harwell graphite-moderated reactors, but so far no reactors in Britain have had automatic starting-up installed as a permanent part of the instrumentation. By introducing a third controlling term proportional to dP/dt, i.e. a function of absolute power, the rate of approach to the demanded level over the last decade or so

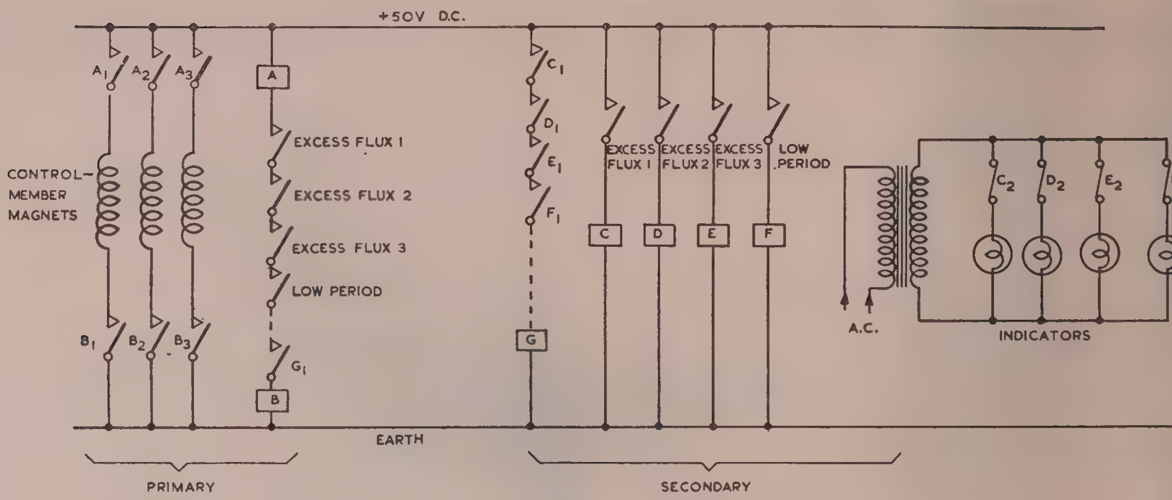

Fig. 11.—Simplified arrangement of shut-down circuits.

can be considerably slowed down compared with that resulting from the 2-term controlled start-up described above. This may be advantageous in some reactors operating at high temperatures, where it is desirable to avoid large temperature gradients occurring between the fuel elements and other parts of the system which have much longer thermal time-constants.

(6) SAFETY

(6.1) Interlocks

In starting and operating a nuclear reactor at power it is essential that the necessary operations of control should be carried out according to a prearranged sequence. It is the function of the control interlock circuits to ensure that this correct sequence is followed and that it cannot be violated in any way. In addition to the normal control interlocks there are many other conditional circuits which govern operations during, say, a maintenance period. For instance, it may be required to carry out a test on the satisfactory functioning of the regulating rods without first going through all the preliminary motions dictated by the normal interlocks. The maintenance interlocks are brought into play here, and movement of the regulating rods is permitted, but only subject to the prohibition of other control operations.

Interlock circuits therefore tend to be peculiar, especially in detail, to a particular type of reactor. In experimental reactors, where changes in the operating sequence may be required from time to time, it is customary to have access to the interlock circuits behind a locked panel, such that duly authorized alterations can be made with a minimum of trouble.

(6.2) Shut-Down Circuits

This part of the safety circuits is designed to shut the reactor down automatically on the occurrence of a serious fault. Typical faults in this category are listed under the appropriate heading in Fig. 2; these are faults of a general nature and are applicable to most reactors. Should a serious fault occur, the relevant detector initiates a sequence of electrical events which terminates in an interruption of the current supply to the hold-on electromagnets of the control members, permitting them to drop into the core and shut down the reactor. It is a point of safety philosophy at Harwell that this interruption of current should be brought about in at least two different ways.

A skeleton arrangement of the shut-down circuits used on a number of small experimental reactors at Harwell is shown in Fig. 11. The circuits are arranged in two groups, known respectively as primary and secondary and corresponding to the alternative ways of interrupting the magnet currents as mentioned above. The primary safety line consists of a series arrangement of relay contacts controlled by the outputs of d.c. amplifiers measuring neutron-flux level, by the output of the differentiating section of the logarithmic flux channel, measuring reciprocal period and by other detectors and instruments within the shut-down category. This safety line is monitored at the top and the bottom by the relays A and B, and contacts of these relays are included in the control-member magnet circuits, so that the control members cannot be raised unless the primary line is complete; conversely, should a break occur in the primary line during operation, they will drop in and shut down the reactor.

The secondary shut-down group comprises a large number of individual parallel circuits arranged in this way primarily to permit identification of the particular fault causing the shut-down. Duplicate relay contacts controlled by the shut-down amplifiers, by the reciprocal-period signal, etc., are monitored individually by the relays C, D, E, F . . . Contacts of these relays are then connected in a series circuit which is monitored by relay G, which operates a contact in the main primary line. Thus the operation of any one of the secondary shut-down circuits will also break the primary line via contact G_1 and cause the release of the control members. By using duplicate contacts on relays C, D, E, F . . ., lamp indication of particular faults can be obtained and an audible alarm can be brought into operation. The relays controlled by the fault-detecting instruments, although not shown on the diagram, are of the non-self-resetting type. This is necessary to preserve the fault identification, since the fault itself may disappear after the reactor shuts down, e.g. excessive flux level. Manual reset is adopted.

All relays are normally energized when the safety lines are complete, because the majority of faults likely to occur in the circuits or relays themselves will result in the relay coil being de-energized. This type of failure will shut down the reactor, and is generally referred to as 'failure to safety'.

In addition to the measure of duplication provided by the primary and secondary circuits, it is customary on the less-reliable fault detectors to introduce some further duplication. This is particularly so on the neutron-flux-operated devices,

because fairly complex electronic circuits are required between the detectors and the relays in the shut-down circuits. These electronic circuits cannot be made completely reliable, and this is the reason for the additional excess-flux relays shown in Fig. 11.

The arrangement of shut-down circuits described has proved quite satisfactory on the smaller experimental reactors. The principal disadvantage, however, is that instrument failure, particularly electronic-instrument failure, can shut down the reactor. It is not possible to prevent the safety-measuring instruments failing in this way, and so it has become a part of the safety-circuit code to try to design them so that they will always fail to safety, and to overcome the inconvenience of accidental shut-down by arranging that at least two channels must operate to initiate a control-member drop. This is achieved by paralleling relay contacts in the safety lines. One channel operating can be arranged to give a warning with identification. A safe and economical arrangement results if three shut-down channels of one type are used, so that operation of any two brings about a shut-down. One instrument can still fail to danger (i.e. relay permanently energized), but the remaining two will break the safety line when the need arises. This combination also allows each instrument in turn to be tested *in situ* without danger of accidental shut-down.

The philosophy of failure to safety in shut-down instruments has resulted in the development at Harwell of two new circuits for excess-flux-level instruments, which have a high inherent degree of failure to safety should an instrumental fault occur. The first, which is shown schematically in Fig. 12, comprises a conventional feedback d.c. amplifier with energized relays A and B in the long-tailed-pair anodes. The circuit is designed so that both relays remain energized throughout its linear operating regime. The trip or shut-down level is reached when diode D_1 'catches' the output-valve cathode at earth. Thereafter the feedback disappears, causing the long-tailed-pair circuit to go rapidly out of balance and de-energizing relay A. Diode D_2 will cause a similar trip action in the opposite direction. The relay contacts are connected in series and any circuit fault, other than an open-circuit of the diode D_1, will cause the trip action to occur.

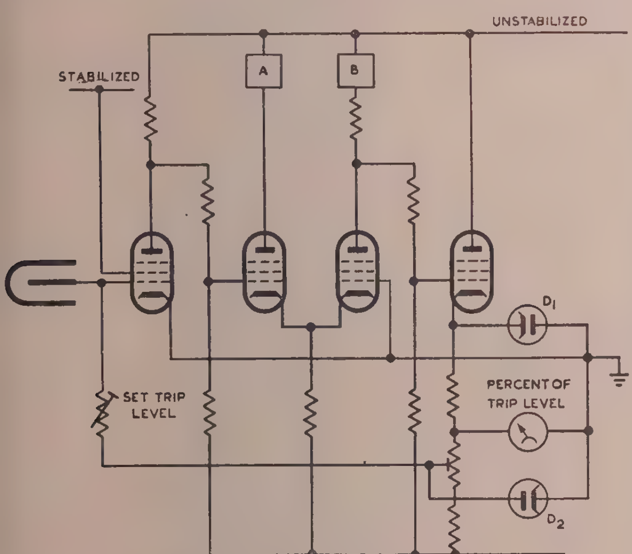

Fig. 12.—D.C. shut-down amplifier.

The principle of the second circuit is shown in Fig. 13. This comprises a high-gain a.c. amplifier with a phase-sensitive rectifier and a polarized relay connected to the output. The input to the amplifier is an alternating voltage obtained by mechanically chopping the difference between a reference voltage defining the trip or shut-down level and the voltage across the ionization-chamber load resistor. When the latter reaches the reference voltage, the output of the a.c. amplifier drops quickly to zero and de-energizes the polarized relay. Should the ionization-chamber voltage exceed the reference value for a short time, the phase-sensitive rectifier prevents the relay being re-operated. D.C. heating of the valves is necessary to guard against possible heater-to-cathode short-circuits.

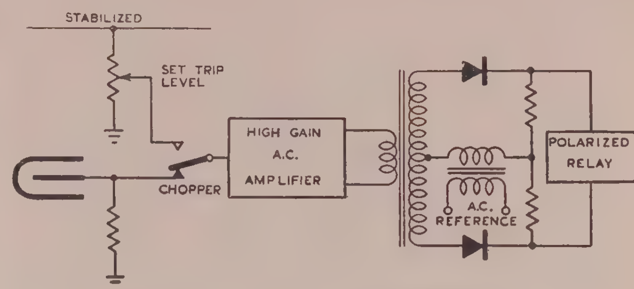

Fig. 13.—A.C. shut-down amplifier.

(6.3) Warning Circuits

This part of the safety circuits is intended to provide visible indication and audible warning of the occurrence of faults or abnormal conditions which are not considered sufficiently serious to initiate an automatic shut-down. Typical faults in this category are listed under the appropriate heading in Fig. 2, but here, more so than in the case of shut-down faults, this list is likely to be very considerably extended for a particular type of reactor by warning faults which are peculiar to that type. Because they are warning faults and not shut-down faults, the emphasis on extreme circuit reliability is not so important as before. The warning circuits are usually identical to the secondary group of shut-down circuits described in Section 6.2.

(7) CONCLUSIONS

Considerable progress has been made in recent years in the development of special instruments and circuit techniques for nuclear-reactor control and safety. Much, however, remains to be done, and this is particularly so in connection with wide-range neutron-flux detectors and equipment associated with the automatic starting-up and control at power level. The problems of overall control on power-producing and propulsion reactors are formidable, and much experimental work extending over a considerable period will be necessary before these problems are solved.

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[The discussion on the above paper will be found on page 607.]

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Mar. 1956

THE CONTROL OF NUCLEAR REACTORS

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SUMMARY

The physical principles of nuclear reactors which affect the design of their control and instrumentation are described. Data are presented for the kinetic behaviour of the neutron flux for reactivity changes in a variety of reactor types. The nuclear reactions inherently produce various nuclides, and the effects of these on reactor control and operation are discussed. These nuclides include the delayed-neutron emitters, which cause a slowing down of the reactor kinetic response; β- and γ-emitters, which continue to produce heat for a long time after the neutron reactions producing them have been shut down; and the fission-product poisons. Reasons are given for the system of neutron-flux instruments normally used, and details are given of the principles of design of the various types of instrument.

LIST OF PRINCIPAL SYMBOLS

n = Neutron population of reactor.
n_0 = Initial value of n.
K_∞ = Reproduction constant of an infinite reacting medium.
K_{eff} = Effective reproduction constant.
S = A 'source' term, n/sec.
$T_{1/2}$ = Half-life of an atom, sec.
β = Fraction of neutrons appearing as delayed neutrons.
i = Serial of delayed-neutron precursor elements.
μ_i = Fraction of delayed neutrons of the ith type.
ρ = Reactivity.
K_{ex} = Excess reproduction constant.
T_ε = Reactor period, or ε-folding time, sec.
T_D = Doubling time, sec.
δK_{eff}; δK_∞ = Small increment in K_{eff}; K_∞.
ρ_j = Reactivity change associated with a physical change j.
ρ_c = Reactivity change associated with a control-rod change c.
α = Reciprocal of reactor period = $1/T_\varepsilon$, sec^{-1}.
λ_i = Disintegration constant for precursors of the ith type, sec^{-1}.
r_i = Total number of atoms of precursors of the ith type.
τ^* = Mean life-time of prompt neutrons.
τ = Average time between successive neutron generations.
m = Number of delayed-neutron groups in fission process.
ϕ = Neutron flux, n/cm^2/sec.
T_u = Uranium fuel temperature, deg C.
T_m = Moderator temperature, deg C.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Cox and Mr. Walker are at the U.K.A.E.A. Atomic Energy Research Establishment.

(1) INTRODUCTION

The feasibility of reactor control depends on several complex nuclear-physical phenomena. While the basic physics of these phenomena are not of immediate interest to the control engineer, their effects are of primary importance. Because of the wide scope of the subject, the paper is confined to a recapitulation of certain basic physical concepts and their influence on the controllability of nuclear plant, illustrations being drawn from reactors built, designed or studied by the U.K.A.E.A. since 1946. The reactors embrace a wide variety of types and of complexity, according as they are intended for experimental, plutonium-production or power-generation purposes. The philosophy of control has developed in step with the construction of these reactors, and the paper is intended to present a broad picture of its present state.

(2) THE FISSION CHAIN REACTION

A nuclear reactor may be broadly defined as a physical system containing fissile material, assembled so as to make the neutron-triggered fission process self-sustaining, by employing the secondary neutrons emitted at fission to cause further fissions—the so-called 'chain reaction'. The growth or decay of neutron flux in such a system will depend on the ratio of neutrons between one generation and the next; this ratio is known as the effective reproduction constant, and depending on whether this constant is greater than, equal to or less than unity, the system is known as super-critical, critical or sub-critical.

In one generation the number of neutrons increases by a factor $(K_{eff} - 1)$, since one neutron is required to initiate the next fission, and hence the generation rate due to fissions with n neutrons present will be

$$\frac{dn}{dt} = \frac{n(K_{eff} - 1)}{\tau} = \frac{nK_{ex}}{\tau} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $K_{ex} = K_{eff} - 1$ and τ is the average time between successive generations.

In all assemblies containing fissile material there is also present a continuous injection of neutrons into the system from spontaneous fission or from other neutron sources. If the strength of this 'source' term is S neutrons per unit time, eqn. (1) becomes

$$\frac{dn}{dt} = \frac{n(K_{eff} - 1)}{\tau} + S \quad . \quad . \quad . \quad . \quad . \quad (2)$$

(2.1) The Reactor Critical

Criticality is defined as the state in which $K_{eff} = 1$. Thus, in a critical reactor it is seen from eqn. (2) that

$$dn/dt = S \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

i.e. the neutron population (and hence the power) of the system is not constant, but increases at a rate equal to the source strength. This steady generation of energy by the reactor, together with the energy injected by the source, gives rise to a steadily increasing power output. To keep this statement in proper perspective it

may be noted that the spontaneous fission rate in natural uranium is about 26 fissions/g/h, and since the energy released per fission is $3\cdot2 \times 10^{-11}$ joule, the spontaneous power of 1 g of natural uranium is $2\cdot3 \times 10^{-13}$ watt. Thus, in Bepo, which contains 4×10^7 grammes of natural uranium, the spontaneous power is about 10^{-5} watt and therefore the power would increase at 10 μW/sec when $K_{eff} = 1$ in the absence of delayed neutrons.

(2.2) The Reactor Sub-Critical

If we consider the sub-critical reactor in which $K_{eff} < 1$, the neutron population will decrease and will eventually stabilize when $dn/dt = 0$, i.e.

$$0 = \frac{n(K_{eff} - 1)}{\tau} + S$$

$$\frac{n(1 - K_{eff})}{\tau} = S$$

$$\frac{n}{\tau} = \frac{S}{1 - K_{eff}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and the reactor behaves as a multiplier of source neutrons by a factor $1/(1 - K_{eff})$.

This concept is of importance when considering the instrumentation and control of a reactor in the sub-critical phase. For instance, if the neutron flux of a sub-critical reactor is measured and is, say, 50 times as great as the value calculated from spontaneous fission rate, the K_{eff} of the reactor is 0·98.

(2.3) The Reactor Super-Critical

Integration of eqn. (2) gives

$$n = \left(n_0 + \frac{S\tau}{K_{ex}}\right)\varepsilon^{K_{ex}t/\tau} - S\frac{\tau}{K_{ex}} \quad . \quad . \quad . \quad (5)$$

If $S\tau/K_{ex}$ is large n will increase very rapidly with time and the source term St is very rapidly swamped. As soon as the source contribution becomes insignificant the rise is a pure exponential. The mean neutron generation time will vary with the type of reactor, but is of the order of 10^{-3} sec for thermal reactors (i.e. reactors where the neutrons are slowed down by a moderator to the thermal energy level of their surroundings, i.e. about 1/30 eV). Thus, for a system in which K_{eff} is very slightly larger than unity (say 1·005) and in which the mean generation time is 10^{-3} sec, the neutron population will increase by a factor of ε^5 ($\simeq 150$) in 1 sec. This rate is quite uncontrollable, and such a system is made controllable by the fact that all the neutrons arising from a fission do not appear immediately. A small fraction, varying from 0·75 to 0·25 % depending on the fissile material used, arise as the result of radioactive decay of fission products excited by the fission to a highly unstable state. The net effect of these delayed neutrons is to increase considerably the mean generation time to more controllable values.

(3) REACTIVITY

(3.1) Definition of Reactivity

The reproduction constant of a reacting assembly is best calculated on the assumption that the assembly or array extends to infinity in all directions. This gives rise to a term known as the infinite reproduction constant, K_∞, which will be larger than that achieved in practice by an amount dependent on the leakage of neutrons from the system. If the system is specified dimensionally, thus fixing the leakage, there is an effective reproduction constant which must be made equal to unity for the chain reaction to be self-sustaining and in equilibrium.

If the reactor is divergent the excess of effective reproduction constant above unity may be used as a measure of this divergency; this excess reproduction constant, K_{ex} has already been defined.

For convenience, a term 'reactivity' is introduced, defined as

$$\rho = \frac{K_{ex}}{K_{eff}} = \frac{K_{eff} - 1}{K_{eff}} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

since this quantity bears a fairly simple mathematical relationship with the reactor period, which is the time required for the reactor to multiply its neutron flux by a factor ε. In the instrumentation of a reactor, reactivity is measured in terms of period, and for operating convenience period is translated into doubling time, which is the time taken for the flux to be doubled; thus

$$\text{Doubling time} = \log_\varepsilon 2 \times \text{period}$$

$$\text{i.e. } T_D = 0\cdot693 T_\varepsilon$$

It is important to appreciate the different significances of ρ and K_{ex}, for it has become fairly common practice in the literature to regard the two quantities as identical, since K_{eff} must be very nearly unity in a system under control. The importance lies in the fact that basic nuclear calculations are made in terms of the effect which any process leading to a change of reactivity will have on K_∞, which may be as high as 2 in highly enriched systems; changes in K_∞ are related to changes in K_{eff} by

$$\frac{\delta K_\infty}{K_\infty} = \frac{\delta K_{eff}}{K_{eff}} = \frac{K_{eff} - 1}{K_{eff}} = \frac{K_{ex}}{K_{eff}} = \rho \quad . \quad . \quad . \quad (7)$$

The term 'excess K' is ambiguous, because it may mean δK_∞ or δK_{eff}, whereas reactivity as defined is unambiguous and should therefore be used in preference.

(3.2) 'Units' of Reactivity

Reactivity is a fraction and therefore dimensionless, but it has been found convenient to ascribe names to various values of reactivity, which values have then tended to be regarded as 'unit reactivity'. A variety of so-called 'units' has originated in different countries, and it may be worth while to describe them.

In the United Kingdom a reactivity of 10^{-2} is said to be 1 'nile', the sub-unit in common use being 10^{-5} = 1 millinile. In France this latter is called a 'p.c.m.' (pour cent mille). In Canada a reactivity of 10^{-3} is called a 'milliK'. The United States has evolved two names: in one case 'unit reactivity' is taken as that reactivity which will give a reactor a period of 1 hour, and is called an 'inhour'. Although theoretically a good unit, this is misleading practically, since the directly inverse proportionality between period and reactivity holds true only for small changes of the latter about the datum chosen (in this case T_ε = 3 600 sec). The second American 'unit' is the 'dollar', being that reactivity

Table 1*

DELAYED-NEUTRON YIELDS IN VARIOUS FUELS

Delayed-neutron half-life, $T_{1/2}$	Yield, $\mu_i\beta$			
	U^{233}	U^{235}	U^{238}	Pu^{239}
sec	%	%	%	%
55·6	0·029	0·023	0·021	0·009
22·0	0·080	0·154	0·216	0·069
4·51	0·116	0·197	0·341	0·078
1·52	0·065	0·223	0·586	0·069
0·43	0·011	0·079	0·276	0·015
0·05	—	0·023	—	—
Total delayed neutrons (β)	0·301	0·699	1·440	0·240

* These abundances and half-lives of the shorter-period delayed neutrons are exceedingly difficult to measure accurately, and the preferred data vary from time to time as more refined experiments are carried out. Figures quoted here should therefore be only taken as a guide showing orders of magnitude.

t which the chain reaction is self-sustaining on prompt neutrons lone. This has the disadvantage of being different for different ssile materials, as can be seen from totals of percentage delayed eutron yield quoted in Table 1.

(3.3) Methods of Controlling Reactivity

Control of a reactor is effected by changing reactivity to allow s neutron flux to grow or decay to a new desired value and eturning the reactivity to zero as this new value is reached. The hange may be made in several ways, classically by the removal om or addition to the system of some neutron-absorbing edium such as cadmium, boron or hafnium, which competes for e neutrons required to sustain the chain reaction. Other ethods are the addition or removal of fissile material, or the teration of neutron leakage from the system. These various ethods of control are dealt with more fully in the companion aper by Lockett.

Finally, there are a large number of factors affecting the reprouction constant which are inherent in the system and dependent, ot only on time, but on the previous history of operation. Such fects include transient poison build-up, fuel depletion, temerature change, etc.

(3.4) Concurrent Reactivity Control Changes

Consider an infinite reacting medium with reproduction conant K_∞. If the conditions are varied, to produce a reactivity hange ρ_1 (e.g. the medium is given a finite size and hence leakage introduced), the effective reproduction constant will become

$$K_{eff\,1} = K_\infty + \delta K_\infty \equiv K_\infty\left(1 + \frac{\delta K_\infty}{K_\infty}\right) = K_\infty(1 + \rho_1)$$

further reactivity change ρ_2 (e.g. introduction of an absorber) ill alter $K_{eff\,1}$ to a new value $K_{eff\,2}$, where

$$K_{eff\,2} = K_{eff1} + \delta K_{eff1} = K_{eff1}\left(1 + \frac{\delta K_{eff1}}{K_{eff1}}\right) = K_{eff1}(1 + \rho_2)$$
$$= K_\infty(1 + \rho_1)(1 + \rho_2)$$

he combined effect of concurrent changes in reactivity is therere multiplicative, and we may write the result of n such hanges as

$$K_{eff} = K_\infty \prod_{j=1}^{n} (1 + \rho_j) \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

This expression is used in the calculation of the control which must be invested in a safety mechanism whose steady-state effect must be made greater than the sudden removal of other effects specified by particular factors in the equation. The use of reactivities as factors rather than additions becomes important when they are large and in reactors where K_∞ is large, such as the Dido class, where $K_\infty \simeq 1 \cdot 79$ (K_∞ for a Bepo class reactor would be about $1 \cdot 05$).

As an example, consider a reactor with a K_∞ of $1 \cdot 79$ and a leakage reactivity of $-0 \cdot 30$, and determine ρ_c, the reactivity investment required on control elements to hold the reactor critical with no other reactivity losses present.

We have $\qquad 1 \cdot 79(1 - 0 \cdot 30)(1 + \rho_c) \leqslant 1 \cdot 00$

i.e. $\qquad -\rho_c \geqslant 0 \cdot 202$

It would be good practice to add a 25% safety margin and provide control rods such that $\rho_c = -0 \cdot 253$.

This safety margin may appear very small to the average engineer, but a study of the response of a reactor to such reactivity changes shows there is little to be gained in speed of shut-down by exceeding this margin.

(4) REACTOR POWER

So far it has been tacitly assumed that reactor power and neutron flux are directly proportional, and in the steady state ($K_{eff} = 1$) this is certainly the case, since the heat output of the reactor arises from the annihilation of matter occurring with every fission. For uranium 235 (at present the most important nuclear fuel) the exchange rate is of the order of 200 MeV of energy per fission. The distribution of this energy among the end-products of the fission process is given in Table 2. There appears to be no reason for assuming any significant difference in

Table 2

Distribution of Fission Energy in Uranium 235

	Energy, MeV
Kinetic energy of fission fragments ..	167
Energy of fission γ	5
Kinetic energy of fission neutrons ..	5
Energy of β decays	5
Energy of γ decays	7
Neutron-capture γ energy	8*
Total energy	197*

* Dependent on the nuclides which capture the fission neutrons.

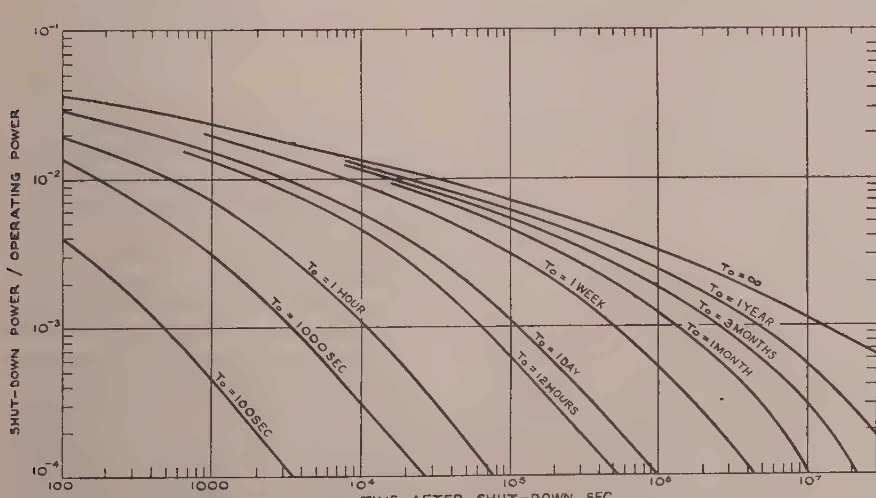


Fig. 1.—Fission-product heat from irradiated uranium.

T_0 = Operating time.

this distribution for the other possible nuclear fuels, uranium 233 or plutonium 239.

In terms of normal engineering units 200 MeV is approximately $8{\cdot}9 \times 10^{-18}$ kWh. All the fission energy except that of the fission-product β and γ decays is released at the instant of fission. The latter, representing about 6% of the total, make their contribution to the released energy of the system independently of the continued presence of neutron flux. Fig. 1 shows the time

reaction directly but are diverted into highly excited fissi product elements which form the precursors for subseque delayed-neutron emission. If photo-neutron reactions such occur in systems containing heavy water or beryllium are co sidered, there may be up to 13 or 14 of such delay groups. Th solution of the kinetic problem is obtained by considering th rate of growth of neutron flux and of precursor elements.

Thus:

Rate of increase of neutron density = Rate of increase due to reproduction constant − Rate of loss of neutrons into precursor elements + Recovery of neutrons from decayed precursors + Appearance of neutron spontaneously or from ou side sources . . . . . . (1

Also

Rate of increase of concentration of the ith precursor element = Gain of element due to its share of second term of r.h.s. of eqn. (11) − Decay of element to release of neutrons . . . . . . (1

dependence of this phenomenon and the effect of different operating times.[1] It is therefore most important to appreciate the difference between neutron power and thermal power in a reacting system. While the reactor is critical and running at steady power the two are of necessity the same, but as soon as K_{eff} changes, a time-dependent discrepancy will appear. The most important effect this has on reactor technology is to make standby cooling necessary. More especially, this standby cooling has to be driven from a guaranteed supply of the utmost reliability, since one of the fault conditions which must be made to reduce reactor thermal output as quickly as possible is failure of main coolant, which may result from coolant-circulator supply failure. In very-low-power reactors this fission-product heating may be removable by natural convection, conduction or radiation, but these methods are of little avail in a plant operating in the megawatt region. This, of course, is primarily a matter for the thermodynamics section of the design team, but the implications are also important in a study of overall control of a power-producing reacting system, more especially if variable-load-output operation is envisaged.

(5) THE DEPENDENCE OF REACTOR CONTROL ON DELAYED NEUTRONS

Having shown that there is rather more in reactor kinetic behaviour than is indicated in eqns. (1)–(4), and introduced the concept of reactivity, we now consider how reactivity is measured and what factors influence the relationship between the measurement and its interpretation.

Reactivity is associated with neutron-flux changes, and it is therefore by measuring neutron flux and its derivatives that we measure reactivity. In the range of positive reactivities the neutron flux diverges exponentially according to a law of the form

$$n = n_0 \varepsilon^{\alpha t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Thus a measurement of α, i.e. the reciprocal of reactor period, is the first step in a measurement of ρ. Rearranging eqn. (9) gives

$$\alpha = \frac{d}{dt}\left(\log_\varepsilon \frac{n}{n_0}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and the basic period meter therefore comprises an apparatus for the logarithmic measurement of neutron flux followed by a differentiating circuit: the implications of these techniques on electronic design are discussed in Section 9.

It remains to establish the connection between reactor period and reactivity. In a given number of fissions, a small fraction, β, do not produce their one-neutron contribution to the chain

Expressed mathematically these equations become

$$\frac{dn}{dt} = \frac{n(K-1)}{\tau^*} - \frac{\beta n}{\tau^*} + \sum_{i=1}^{m} \lambda_i r_i + S \quad . \quad . \quad . \quad (1$$

and

$$\frac{dr_i}{dt} = \frac{\mu_i \beta n}{\tau^*} - \lambda_i r_i \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

Values of $\lambda_i \left(= \frac{0{\cdot}693}{T_{1/2}}\right)$ and $\mu_i\beta$ can be obtained from Tables and 3.

Fig. 2 shows the decay chain which gives rise to the longes delayed neutron from an isotope of bromine, Br^{87}. Th 22 sec delayed neutron comes from an isotope of io dine.

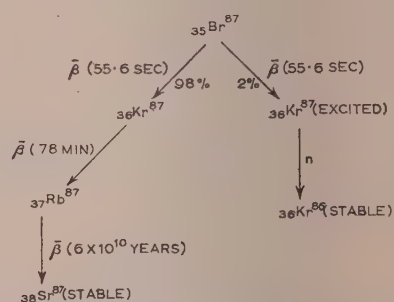


Fig. 2.—55·6 sec neutron from bromine 87.

Table 3 shows the additional delayed-neutron yield fro photo-neutron reactions in a uranium 235 heavy-water system

It is customary in the literature[4] to simplify the above by co sidering all the delayed neutrons to be in one group having o mean reappearance rate. This simplifies the mathematics co siderably and is quite useful for quick checks on period/reactivi relationships when δK is very small, but it cannot be too strong emphasized that this is an approximation and should be us with caution. The solution of the large number of simultaneo differential equations [eqns. (13) and (14)] has been made relative simple by the development of analogue computers, and it is th authors' opinion that such equipment is an essential tool of reactor control team. The solution of these equations in term of ρ is given in detail in the literature,[4,5] and is merely quoted her

It is

$$\rho = \frac{\tau^* \alpha}{K_{eff}} + \sum_{i=1}^{m} \frac{\alpha \mu_i \beta}{\alpha + \lambda_i} \quad . \quad . \quad . \quad . \quad (1$$

where α has the dimension of inverse time.

Table 3*

DELAYED PHOTO-NEUTRON YIELD IN U^{235}–D_2O SYSTEM

Half-life, $T_{1/2}$	Yield, $\mu_i\beta$
sec	%
2·49	0·0207
40·9	0·0065
141·4	0·0022
454	0·0011
$1{\cdot}62 \times 10^3$	0·00067
$5{\cdot}99 \times 10^3$	0·00074
$1{\cdot}57 \times 10^4$	0·00010
$1{\cdot}89 \times 10^5$	0·00003
Total, β	0·032

* These abundances and half-lives of the shorter-period delayed neutrons are exceedingly difficult to measure accurately, and the preferred data vary from time to time as more refined experiments are carried out. Figures quoted here should therefore be only taken as a guide showing orders of magnitude.

Replacing α by $1/T_\varepsilon$ we have

$$\rho = \frac{\tau^*}{T_\varepsilon K_{eff}} + \sum_{i=1}^{m} \frac{\mu_i\beta}{1 + \lambda_i T_\varepsilon} \quad . \quad . \quad . \quad . \quad (16)$$

relating reactivity to the reactor period T_ε.

Table 4 gives values of τ^* for various reactor types.

Table 4

MEAN NEUTRON LIFETIME FOR VARIOUS REACTORS

Reactor	Type	τ^*
		sec
Bepo	Thermal, natural uranium, graphite moderated	$1{\cdot}4 \times 10^{-3}$
Dido	Thermal, uranium 235, heavy-water moderated	$1{\cdot}4 \times 10^{-3}$
Pippa.. ..	Thermal, natural uranium, graphite moderated	$\sim 10^{-3}$
Zephyr ..	Fast, plutonium 239, natural uranium	$\sim 10^{-7}$
Lido	Thermal, uranium 235, light-water moderated	$\sim 5 \times 10^{-5}$
Zeus	Fast, uranium 235, natural uranium	$\sim 10^{-7}$

Fig. 3(*a*) shows the relationship between ρ and T_ε for typical fast and thermal systems using uranium and plutonium as fuel; it will be noticed that the relationship between ρ and T_ε is almost identical for all cases so long as ρ is less than the delayed fraction, β, for the fuel concerned. This is shown by an enlargement of this section of the curves in the Figure and is given in Fig. 3(*b*). The significance of this is that fast and thermal reactors are indistinguishable from the operator's viewpoint, each having the same response to similar changes in control movement. The divergence of the curves for values of $\rho > \beta$ indicates the increased importance in fast-reactor design of ensuring that under no circumstances are reactivities as high as this ever possible.

(6) CHANGES IN NEUTRON ECONOMY DURING OPERATION

As indicated in Section 3.3, changes in reactivity occur inherently in a reacting system without control intervention. Some of these changes in neutron economy are not advantageous, but all have a very significant place in the control of a reactor and in the mode of its operation.

(6.1) Depletion of Fuel (Burn-up)

The fissile material is the fuel of the reactor, and as fissions occur there will generally be fewer fissionable atoms available. This process is known as depletion, or burn-up, and the extent to which it can be carried before recharging the fuel system is a major factor in reactor operating economy. One requirement is the removal of depleted fissionable material from the reactor, since its continued presence implies loss in reactivity due to loss of fissionable atoms and an increasing concentration of neutron-absorbing fission products.

The fuel life permissible will depend on the depletion which can be accepted. Thus, in Dido, if the fuel is used to 20% burn-up, one-fifth of the uranium 235 atoms will be used before reprocessing. At 10 MW there will be $3{\cdot}1 \times 10^{17}$ fissions per sec, and the uranium 235 will be depleted at the rate of

$$\frac{3{\cdot}1 \times 10^{17} \times 235}{6 \times 10^{23}} \text{ g/sec*}$$

$$= 1{\cdot}25 \times 10^{-4} \text{ g/sec}$$

The fissile material in the core is 2·5 kg of uranium 235 in the form of enriched material. Hence, 20% burn-up would be reached after 500 g had been burnt, i.e. after $500/(1{\cdot}25 \times 10^{-4}) = 4 \times 10^6$ sec—some six weeks of continuous operation at 10 MW.

(6.2) Temperature Effects

Changes in temperature of the materials of a reactor alter the reproduction constant (and hence the reactivity) by altering the nuclear physical constants (such as the energy level of thermalized neutrons, the mean free paths of the various nucleons, etc.) and also the physical dimensions of the system. The effects of temperature changes in the fuel and the moderator are distinguishable, and give rise to temperature coefficients of reactivity for the two materials. In general, these temperature coefficients are negative and so exert a stabilizing influence on the system. Increase in neutron flux will increase system temperatures, which reduces reactivity, and thus tends to restrain the neutron-flux increase. The temperature coefficients vary greatly with the system under consideration, from about -2×10^{-5} per deg C for graphite-moderated heterogeneous systems to about -1×10^{-4} per deg C for heavy-water-moderated homogeneous ones. The loss of reactivity involved in taking a reactor from cold to operating temperatures has to be taken into account and provided for in the size of core designed, and an equivalent K_{ex} must be built in to the system. Furthermore, the recovery of this reactivity as the reactor cools on shutdown has to be allowed for in the design of the safety and control devices. This refers to the steady-state temperature effects, but transient effects will occur as the reactor is taken from one power level to another, and the response in terms of rate of change of reactivity due to transient temperatures will depend on the thermal capacity of the system and the transport lags of heated coolant to and from the primary heat exchanger. Thus, for a study of an overall control system, the basic neutron kinetic equations [(13) and (14)] must be compounded with the multitude of differential equations arising in the heat transfers of the system, e.g. fuel to coolant, coolant to moderator, coolant to secondary coolant in heat exchanger, and it is in this field that analogue-computer techniques are most fruitful. It is fairly easy to change design parameters in an analogue study, thus enabling a wide field of possible designs to be examined rapidly. Once a design has been optimized to within a few per cent, it may then be worth while making a more exact calculation using digital-computer techniques.

* The 6×10^{23} (Avogadro's number) appearing in this fraction is the number of atoms per gramme-atom.

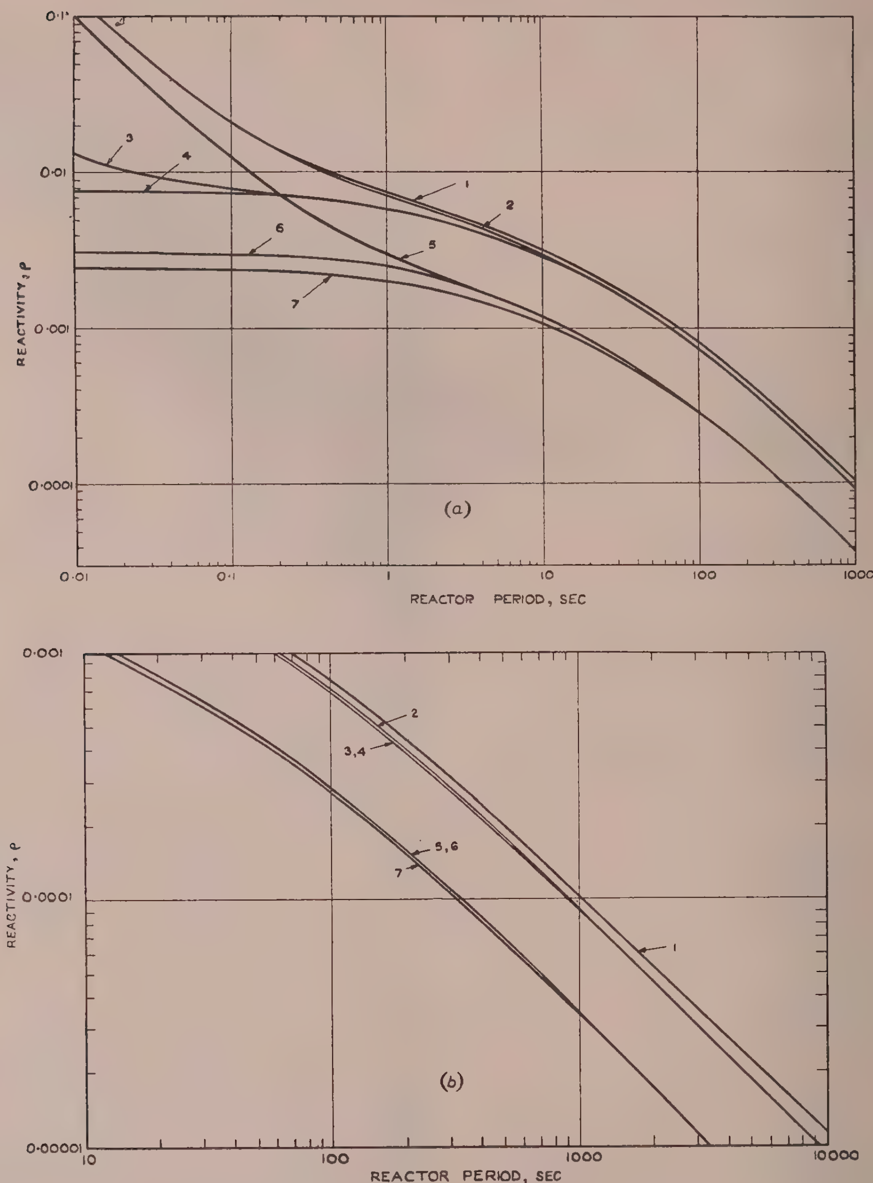


Fig. 3.—Relationship between ρ and T_{ε} for typical systems.

1. Dido.
2. Bepo.
3. Lido.
4. Zeus.
5. Theoretical (plutonium 239, thermal).
6. Zephyr.
7. Theoretical (plutonium 239, fast).

(6.3) Fission-Product Poisons

The most significant fission product from the control aspect is xenon, which has a very high capture cross-section for neutrons. It is not a direct fission product, but arises from the decay of $_{52}Te^{135}$ as shown.

$$_{52}Te^{135} \xrightarrow{\beta(2\,min)} {_{53}I^{135}} \xrightarrow{\beta(6\cdot7\,h)} {_{54}Xe^{135}}$$

and itself undergoes decay:

$$_{54}Xe^{135} \xrightarrow{\beta(9\cdot2\,h)} {_{55}Cs^{135}}$$

and also neutron capture:

$$_{54}Xe^{135}(n, \gamma)\ {_{54}Xe^{136}}$$

In consequence of this mode of formation and decay, the xenon 135 concentration in a reactor at steady flux will build up to an equilibrium in which the formation and decay rates are equal. If the flux level is changed, a new equilibrium will eventually be found, the time taken to reach this being governed by the disintegration rates of the various nuclides. The changes in concentration during such transients may indeed be such as to cause changes in reactivity so large that these cannot eco-

nomically be built in as excess K in the system, and, particularly n high-flux thermal reactors, the phenomenon of 'poison-out' after shut-down has to be accepted as an inherent feature of the system. A chart for the estimation of 'peak' value of xenon poison transient in Dido after a change in flux is given in Fig. 4.

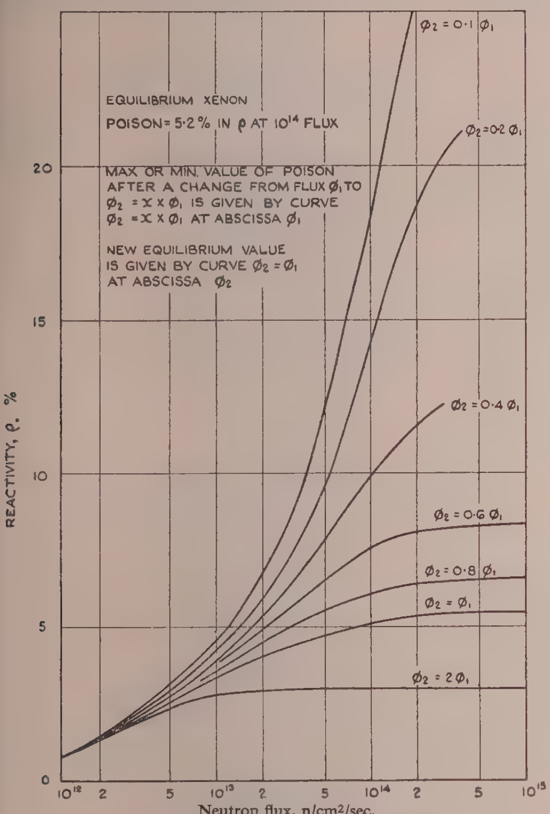


Fig. 4.—Xenon poison in Dido after step change in flux.

n this reactor equilibrium xenon poison at 10^{14} n/cm²/sec is ·2% in reactivity. If, for example, the flux is now suddenly hanged to $\phi_2 = 10^{13}$ n/cm²/sec the poison will build up to about 8% (from curve $\phi_2 = 0 \cdot 1\phi_1$), and will eventually fall again to ts new equilibrium value of 3·5% (from curve $\phi_2 = \phi_1$).

Consider an example of an increase in flux, and suppose that $_1 = 5 \times 10^{13}$ n/cm²/sec and $\phi_2 = 10^{14}$ n/cm²/sec.

Before the change the poison effect is 4·75%. After the hange it falls to a minimum at 3%, thereafter rising again to its ew equilibrium value of 5·2%. The initial rate of increase n reactivity after the change would be of the order of 1×10^{-5} er second, representing a destabilizing factor in the reactor ontrol. The time dependence of such reactivity changes is of he form shown in an earlier paper.[2] The importance of the henomenon increases very markedly as fluxes begin to exceed 0^{13} n/cm²/sec, and apart from its nuisance value as a complete eto on further operation for several hours after such a reactor as been shut down, its effect will be felt in the control if the eactor is required to operate conditionally at part load. This nay well be the case in mobile reactors such as may be designed or ship or aircraft propulsion.

(7) ANALYSIS OF REACTIVITY CONTROL RATES

Since it is by means of reactivity changes that a reactor is controlled, a study must be made of the effect of these changes on the reactor power. This is particularly important for reactor start-up. During the phase of operation when the power due to fission is small, the reactivity of the reactor determines the rate of change of nuclear power: the control elements are therefore accelerator controls. While the reactor is shut down it is impossible to determine by how much the reactivity must be increased to make the reactor critical, since the degree of divergence of the reactor can be observed only through neutron-flux measurements. If the reactivity is increased by a series of discrete steps, at each step the neutron flux will increase suddenly by a certain amount due to prompt neutrons, followed by a slow change due to delayed neutrons, making it difficult to appreciate what reactivity has been reached. It is better to increase reactivity at a uniform rate. It is possible by a fault in operation or in equipment for reactivity to continue to be added to the reactor after the required reactor period has been reached. Some other phenomena or safety devices will come into action at a later time, but the reactor period may then be so short that a large overshoot in power is caused. It is imperative that the corrective action should prevent damage occurring to the reactor, and this demands that the reactor period should not be less than a certain amount before this action takes place. Thus, reactivity should be added at a rate that can be guaranteed, even under fault conditions, not to exceed a safe one. The criterion for determining this maximum safe rate depends considerably upon the design of the reactor. In the next Section, one example is considered where the stabilizing influence is due to the temperature coefficient of reactivity of the reactor—a criterion particularly applicable to power reactors in which the temperature rise is high.

(7.1) Temperature-Stabilized Start-up

As pointed out by Moore, Bowen and others,[2,3] the temperature coefficients of reactivity are usually negative and exert a stabilizing influence on power transients within the range of sensible temperature change. It is possible in the start-up phase to make use of this effect, and start-up rates are proposed which are sufficiently slow for the temperature-controlled reactivity effects to keep pace with the power rise. It will be obvious that the upper limit of rate of power increase to which this will apply will be dependent upon details of plant design, in particular the thermal capacity of the system and the transport lags for coolant between reacting core and primary heat exchanger. Using figures quoted[2] as typical values for fuel and moderator temperature coefficients we have

$$\frac{\delta K}{\delta T_u} = -1 \cdot 6 \times 10^{-5} \text{ per degree C}$$

$$\frac{\delta K}{\delta T_m} = -1 \cdot 25 \times 10^{-5} \text{ per degree C}$$

when T_u and T_m are fuel and moderator temperatures respectively. The combined effect of these two coefficients will be $-2 \cdot 85 \times 10^{-5}$ per deg C. Under steady-state conditions, consider a reactor with a temperature rise in the fuel of 350° C operating at 200 MW. If power changes are sufficiently slow we may assume that equilibrium conditions exist and define a 'power coefficient' of reactivity, which in this case would be

$$\frac{-2 \cdot 85 \times 10^{-5} \times 350}{200} \text{ per megawatt}$$

i.e. $\quad -5 \times 10^{-5}$ per megawatt

The above analysis is a very crude one, intended to show that the right order of power coefficient is being investigated. Fig. 5 shows results of an analogue computation of the power transient in a reactor started up by control movement at an increase of

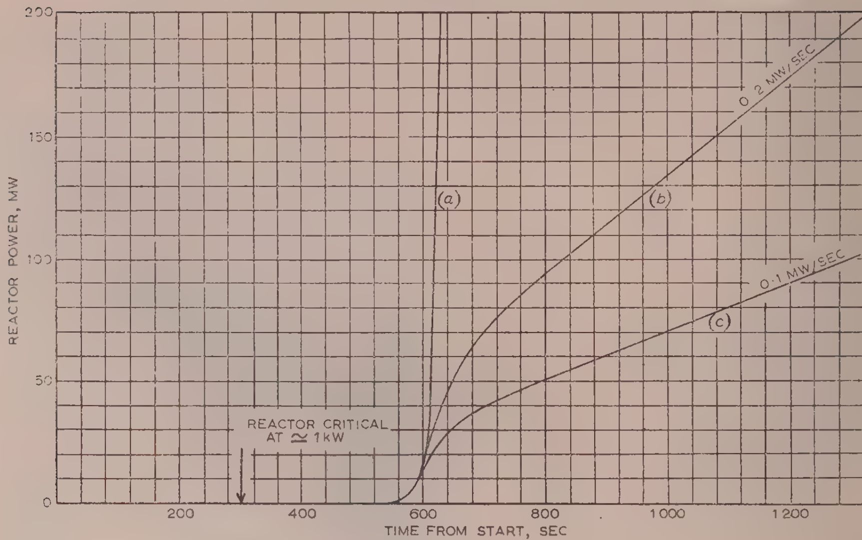


Fig. 5.—Temperature stabilization of start-up.

(*a*) Power coefficient neglected.
(*b*) Power coefficient of -5×10^{-5} per MW.
(*c*) Power coefficient of -10×10^{-5} per MW.

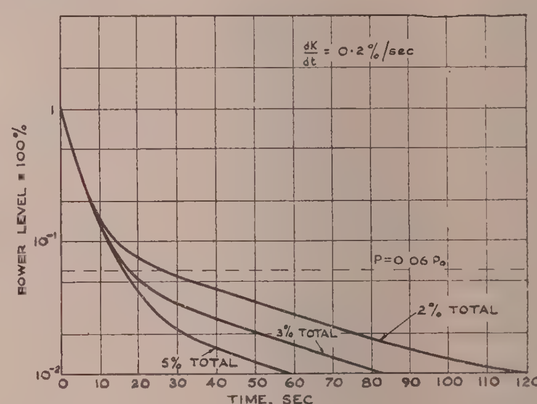
1×10^{-5} in reactivity per second, with power coefficients of -5×10^{-5} and -10×10^{-5} per megawatt. Points of interest are

(*a*) Curve (*a*) shows how the power would increase if the temperature effect were zero. If the shut-down rods were dropped when the power reached 200 MW, the power could reach several times this value before it started to fall, owing to the time of fall of the rods. This might damage the reactor.

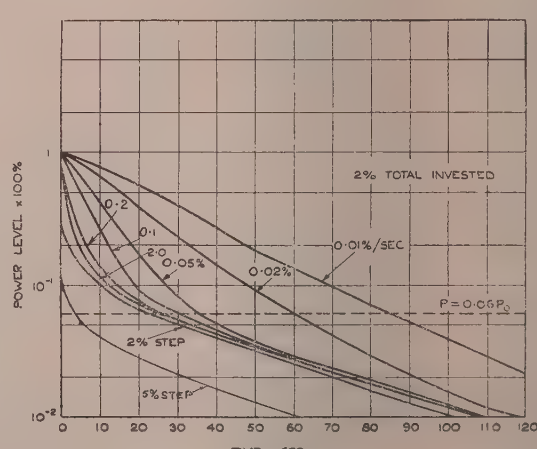
(*b*) With a temperature effect of -5×10^{-5} in reactivity per megawatt the power rises linearly towards 200 MW at only 0·2 MW/sec. There will therefore be no overshoot in power above the 'trip setting'.

(7.2) Rates of Shut-Down

In experimental reactors it has been common practice to date to reduce reactivity by as large an amount as possible in the shortest possible time whenever a fault occurs. This is a sensible thing to do when the major investment to be protected is the reactor itself. In some reactor systems, however, this action might cause more ultimate damage than that which has been prevented. For instance, in a submarine propulsion unit using a high-flux thermal reactor, a sudden shut-down would cause the reactor to 'poison-out' and immobilize the ship for up to two days. Moreover, the heat-generation rate can never be reduced below the fission-product heat rate. The neutron flux will also never fall faster than the 80 sec delayed-neutron period, after the initial prompt-neutron jump has died away, so that in any new reactor design careful consideration must be given to the way in which reactivity is decreased for particular fault conditions. The reactivity can be decreased either in one rapid step or at a uniform rate over a period of time. Figs. 6(*a*) and 6(*b*) show the change in reactor power for a number of different rates and total amounts of reactivity removal, and Fig. 6(*b*) includes two curves for step changes in reactivity. These curves are derived from analogue computations of the kinetic equation only and do not include fission-product heating or take any account of changes in reactivity due to temperature changes or poisons. A broken line drawn at $P = 0{\cdot}06P_0$ indicates the level of fission-product heat. It will be noticed that for a quick fall in reactivity there is a rapid fall in power due to the prompt neutrons, followed by a slower decay due to the delayed neutrons. At very slow rates



(*a*)



(*b*)

Fig. 6.—Application of negative reactivity at controlled rates.

P = Fission-product heat level.
P_0 = Operating power.
(*a*) Total invested, various: application at $-0{\cdot}2\%$ per sec.
(*b*) Total invested, 2%: various rates of application.

e flux falls almost exponentially. Fig. 6(*b*) demonstrates that nen a total of 2% in reactivity is removed the time taken to ach a few per cent of the initial power is very little shorter for a ep change than it is for the slow rate of 0·05% per second. able 5 gives figures for the time taken to reach the fission-oduct heat level for various rates of reactivity removal.

Table 5

TIMES TO FISSION-PRODUCT HEAT LEVEL FOR VARIOUS NEGATIVE REACTIVITY RATES

Total reactivity applied	Application time	Rate	Time to 6% of operating power
%	sec	%/sec	sec
−5	0	∞	3
−3	0	∞	10
−2	0	∞	22
−2	1	2	25
−2	10	0·2	26
−2	20	0·1	30
−2	40	0·05	36
−2	100	0·02	60
−2	200	0·01	85

(8) CONTROL INSTRUMENTATION

(8.1) Necessity for Measuring Neutron Flux

Since the heat generated by a nuclear reactor is due to the ssion of atoms by neutron bombardment, it is natural that instru-nents capable of measuring the neutron density in the reactor hould play an important role in the control instrumentation ystem. In an experimental reactor, where the neutron flux—erhaps at many points within the reactor—is the quantity of rimary interest, this statement needs little elaboration; indeed, ome experimental reactors can be controlled perfectly satis-actorily without any other form of measuring equipment. In power-producing reactor the primary interest is in the rate of otal heat generation, and the necessity of measuring the neutron ux is not quite so obvious. It has been shown in Section 7 hat, in a reactor with a reasonable power coefficient of reactivity, rovided that reactivity is increased slowly, the reactor power pproaches operating levels at a reasonably slow and therefore ontrollable rate. However, it has also been shown in Section 4 hat the rate of heat generation due to the β and γ emission rom various nuclides decays only slowly after the reactor is hut down, so that, if temperature measurements are the only nes made on the reactor, the fact that the reactor is diverging vill be apparent only when the power has exceeded that due to and γ decay. During the period that a reactor is shut down here is no satisfactory method of indicating the reactivity of the eactor: measuring the neutron flux is not sufficiently accurate. or instance, if $K_{eff} = 0·95$ in a natural uranium reactor, the quilibrium value of the neutron power level will be $1/(1 - 0·95)$, e. 20 times the source strength (see Section 2.2). If K_{eff} increases o 0·955 the neutron flux will increase to 22·2 times the neutron ource strength. Thus, a reactivity increase of 0·5% from a K_{eff} f 0·95 results in an 11% increase in neutron flux. However, if he reactivity had increased by 0·5% from a K_{eff} of 0·998, a eactor with uranium 235 fuel would have become divergent with period of 10 sec, resulting in a rapid increase in power level.

Most reactors must be shut down in order that such operations s loading and unloading of fuel can be performed, because it is sually necessary to remove some of the shielding locally for the nsertion of the loading and unloading mechanisms. Thus, the eutron power must not be allowed to exceed a level determined y the health hazard to the operating staff. This will be below the power level due to β and γ decay, and cannot therefore be monitored by temperature measurements: neutron-flux measurements are therefore required. Moreover, it is often difficult to perform such operations as loading or unloading fuel and still keep within the criterion of rate of reactivity addition determined by the self-stabilizing phenomenon described in Section 7.1.

Thus, although the measurement of neutron flux does not provide an accurate indication of the reactivity of a reactor when it is shut down, the measurement becomes increasingly useful as the reactivity approaches and exceeds the critical level, and is essential for the protection of the operating staff during operations when the shielding would be insufficient at normal operating powers. When the power of a power-producing reactor is in the normal operating range, there is less necessity to use neutron-flux measuring equipment.

Under transient conditions a measurement of the neutron flux does not give a measurement of the total rate of heat generation at that instant, because of the time dependence of the heat produced by β and γ decay. At steady power this has been shown in Section 4 to amount to about 6% of the total for uranium 235. Moreover, in a heterogeneous reactor system there are a number of thermal time-constants differing considerably in their value, and thus there is no simple relation with time between any temperature and the power. Preliminary studies of the control of a complete nuclear power station shows the importance of having a method of measuring power that is fast-acting, in order to achieve stable operation. In some types of power reactor it might be quite impossible, with currently used techniques, to measure temperatures sufficiently reliably and quickly to achieve stability. A solution would be to use a neutron-flux measurement for the short-term control of the reactor with an overriding temperature control.

(8.2) Range of Neutron Fluxes

It has been shown in Section 2.2 that when a reactor is subcritical the neutron flux decays until

$$\frac{n}{\tau}(K_{eff} - 1) = - S$$

the reactor acting as a multiplier of the neutron sources in the reactor system.

Most of the materials that act as fuels in a reactor emit neutrons spontaneously. For instance, with natural uranium, uranium 238 is the principal contributor to spontaneous-neutron emission, for it undergoes 26 spontaneous fissions per hour per gramme of material. In a reactor with 100 tonnes of natural uranium this would amount to a source-power level of $2·25 \times 10^{-5}$ watt. If the reactivity of the reactor were such that $K_{eff} = 0·95$, the reactor would act as a multiplier of factor 20 and the neutron power of the reactor would be $4·5 \times 10^{-4}$ watt. If this 100 tonnes of natural uranium were in a graphite-moderated reactor with a normal operating power of 200 MW, the range of power level between sub-critical and full power would be $4·4 \times 10^{11}$.

If the natural uranium were in a heavy-water-moderated reactor the spontaneous fission of the fuel would be dwarfed in magnitude by the so-called photo-neutron background. Heavy water will emit neutrons if it is bombarded by γ-rays with an energy exceeding 2·21 MeV. A number of the fission products of natural uranium have energies greater than this threshold level. One of them, lanthanum 140, is produced by about 6% of all fissions, it has a half-life of 40 h and about 4% of the γ-rays it emits have an energy of 2·4 MeV. Fig. 7 shows a curve of the decay of neutron flux in a heavy-water reactor when shut down by reducing K_{eff} well below unity. It will be noticed that after

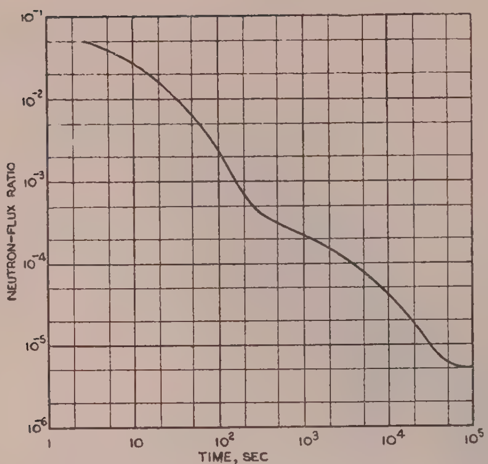


Fig. 7.—Neutron flux after shut-down in a heavy-water-moderated reactor.

an hour the neutron flux is about 10^{-4} of the normal operating level, falling to about 10^{-6} after several days. The level of this photo-neutron background is obviously dependent on the history of its operation, but after the reactor has been operating at full power for a few weeks its level will fall below 10^{-6} of full power only during long shut-down periods. Thus, neutron-flux-measuring equipment covering a range of 10^6 will suffice.

Beryllium is another material with a low γ-energy threshold for the photo-neutron reaction (about 1·67 MeV). It can also be used as a moderator. If a beryllium-moderated thermal reactor were ever constructed, it is to be expected that its range of neutron fluxes would be comparable to those of heavy-water reactors.

In reactors that use a small amount of fuel and are not heavy-water moderated (e.g. Lido, Zephyr and Zeus) the shut-down neutron power might be as low as 10^{-14} of the operating level if spontaneous fission of the fuel were the only source of neutrons. In these types of reactor an artificial source of neutrons is necessary for satisfactory control. Artificial sources are also justified economically in graphite-moderated natural-uranium reactors, because of the simplification of the measuring equipment that they allow.

(8.3) Use of Artificial Neutron Sources

There are two main classes of artificial neutron sources: the first uses the so-called (α, n) reaction with a material like beryllium, which is bombarded with α-particles from a suitable nuclide and thus emits neutrons; the second uses the photo-neutron, or (γ, n), reaction mentioned in Section 8.2. In both classes of neutron source beryllium is the most popular target material, because of its convenient mechanical properties.

(8.3.1) Sources Depending on an (α, n) Reaction.

Any α-emitting nuclide can be used in the source, the most popular being radium, polonium, plutonium and actinium. With radium, each curie results in the emission of about 10^7 neutrons per second. It has a conveniently long half-life, but it suffers from the disadvantage of being a γ-emitter as well as an α-emitter, and therefore poses a handling problem both in its use and in its manufacture. It is also relatively expensive. Polonium has no γ-emission and is therefore easier to handle, but it has a half-life of only 138 days. Plutonium is an attractive material having a half-life of 24 000 years and can be made with a relatively low γ-activity, but the security surrounding this material h hampered its use in neutron sources.

Since α-particles have a relatively short range, the α-emitti material must be in intimate contact with the beryllium. This usually achieved by compacting an intimate mixture of the tw materials in powder form in a suitable container. One curie radium-beryllium so constructed emits 10^7 n/sec. If this is us in a reactor with $K_{eff} = 0{\cdot}95$, it will result in a neutron generati of 2×10^8 n/sec, corresponding to a power level of 2·5 m It should be noted that this power is independent of the mass fissionable material in the system, and where the fuel investme is small it will completely swamp the power arising from spo taneous fission.

(8.3.2) Photo-Neutron Sources.

Since the range of γ-rays is relatively large, there is no ne for an intimate mixture of γ-active material and berylliu Furthermore, there is a variety of nuclides with sufficiently hi γ-energy which can be produced by the irradiation in the react of a non-radioactive material; the source can therefore be ma with stable compounds which need no special handling equi ment. They can then be activated either by placing them another reactor, or in the reactor for which they are intende during the commissioning phase, when special sources and speci measuring equipment are usually necessary. In the latter cas the source can be designed so that it becomes self-sustainin Na^{24}, Sb^{124}, Ga^{72}, Mn^{56}, In^{116} and La^{140} are nuclides whi might be useful as the γ-emitter of a self-sustaining phot neutron source. For this particular application the main intere is in obtaining the maximum rate of neutron emission over t duration of a reasonable shut-down period of the reactor for t minimum loss of reactivity. Sodium carbonate has the highe neutron emission for a given reactivity loss, but has a half-li of only 14·8 h. Antimony is the next best; it has a half-life 60 days, but has a neutron emission of only about one-sixth that of sodium carbonate. For the same loss in reactivi sodium carbonate will give a greater neutron emission for shu down periods up to 40 h: beyond 40 h antimony is the bett material to use.

In Bepo, neutron sources of sodium-carbonate–berylliu and also some of antimony–beryllium are used. Shortly aft the reactor has been shut down the sub-critical power is abo $\frac{1}{2}$ watt (at $K_{eff} = 0{\cdot}97$) compared with the power of abo 300 μW due to spontaneous-neutron emission of the fuel. Th a reduction in the neutron-flux range by more than 1 000 h been achieved with a loss in reactivity due to neutron absorpti by the source materials of about 20×10^{-5}. For natur uranium graphite-moderated reactors with a source in the po tion of mean flux and $K_{eff} = 0{\cdot}96$, the shut-down power 10^{-8} of full power for a reactivity loss of 2×10^{-4} when usi antimony–beryllium, and 10^{-7} of full power for a reactivity lo of 3×10^{-4} when using sodium-carbonate–beryllium.

(8.4) Choice of Neutron Detectors

Abson and Wade give data on the characteristics of the ioniz tion chambers currently available in Britain for reactor contr In these chambers the mean level of the current flowing measured by some form of d.c. amplifier. The chambers pa current proportional to the neutron flux and to the γ-flux, a the maximum range of neutron flux over which one ionizati chamber can be used is determined by the ratio of the neutr flux to the unwanted γ-flux. For an RC/1 type of chamber wi a coating of 500 cm² of boron 10 and filled with hydrogen 15 cm Hg, the current due to the activation of the chamb materials is about $5{\cdot}2 \times 10^{-8}$ of the full-power neutron curre

half an hour after shutting down the reactor, falling to $1 \cdot 6 \times 10^{-8}$ after about 8 h. This represents the maximum range of neutron flux that can be measured by a single ionization chamber. However, the range to be measured may well exceed these limits, and usually does, except in heavy-water-moderated reactors. Two sets of ionization chambers are therefore needed; those used at the lower end of the flux range will need to be retracted into a region of low flux while the reactor is at high power to prevent the activation of the materials of the chamber. During the period in which they are used the induced activity of the chamber is not significant. The criterion is now the sensitivity of the chamber to external γ-radiation. The RC/1 chamber gives the same current in a neutron flux of 80 n/cm^2/sec as in a γ-field of 1 r/h, and by surrounding the chamber with 4 in of 'chemical' lead the γ-level is reduced by a factor of about 300 for a reduction in neutron flux of about $1\frac{1}{2}$. Thus, equal currents would be produced by $0 \cdot 4$ n/cm^2/sec and 1 r/h; the ionization chamber could thus be used if the ratio of n/γ flux was about 4 n/cm^2/sec per r/h, which represents the practical limit that can be achieved with this design of ionization chamber.

If the n/γ flux ratio is worse than this a pulse-counting system may be necessary; here, each pulse produced in the detector is amplified and compared with a bias voltage in a pulse-height selector (or discriminator) and only those pulses higher than a certain level are passed on to the counting circuits. The bias level is set so that pulses due to the detection of neutrons are counted, but pulses due to the detection of γ-rays or β-particles are excluded, the particles being distinguished by the amount of ionization produced in the detector. However, if the γ-flux is sufficiently high, a number of γ-pulses may occur during the resolving time of the equipment and build up to a single pulse sufficiently large to pass the discriminator. This type of system is characterized by an absolute level of γ-background above which the spurious counting-rate rises very rapidly. With proportional counters filled with boron trifluoride and the appropriate counting circuits this absolute level is about 1 kr/h, but with a pulse type of ionization chamber coated with uranium 235 the limiting level of γ-background is much higher. Tests to date have shown that levels of 30 kr/h cause just measurable interference, so the limit is taken tentatively as $0 \cdot 1$ Mr/h, but the practical limit may well be as high as 1 Mr/h. Fig. 8 shows the range of operation of typical neutron detectors. For ionization chambers a limiting value of neutron to γ-ray current of 10 is taken, together with a minimum current of 10^{-12} amp (representing a practical limit for current measurement), and as an upper limit the neutron flux for which 90% of the current is collected with a polarizing potential of 100 volts. For pulse-counting systems 25 counts/sec is taken as the lower limit for satisfactory statistical accuracy and 250 000 counts/sec as the upper limit for reasonable counting losses. The whole area to the left of the line drawn therefore represents the usable field of neutron and γ-fluxes.

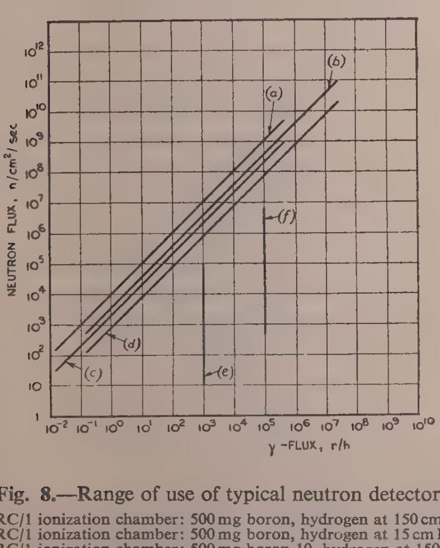


Fig. 8.—Range of use of typical neutron detectors.

(*a*) RC/1 ionization chamber: 500 mg boron, hydrogen at 150 cm Hg.
(*b*) RC/1 ionization chamber: 500 mg boron, hydrogen at 15 cm Hg.
(*c*) RC/1 ionization chamber: 500 mg boron 10, hydrogen at 150 cm Hg.
(*d*) RC/1 ionization chamber: 500 mg boron 10, hydrogen at 15 cm Hg.
(*e*) Boron trifluoride proportional counter.
(*f*) Fission chamber: 140 mg uranium 235.

Mean-current ionization chambers should be used wherever possible, for they are much simpler, cheaper and more reliable than pulse-counting systems, and, in general, the range of use and statistical accuracy is much higher. Ionization chambers using natural boron are obviously cheaper and therefore to be preferred to those using boron 10. For the pulse-counting systems, boron-trifluoride proportional counters are much cheaper than fission chambers and can use somewhat simpler electronic circuits.

(9) THE REACTOR INSTRUMENTATION SYSTEM

Reactor instrumentation techniques have advanced considerably in the past few years. The use of neutron sources has reduced the range of neutron flux between the shut-down state and full-power operation, and improvements in the electronic circuits have reduced the level of neutron fluxes that can be measured under plant conditions. Improvements in the neutron detectors, together with the use of lead shields, has reduced the effects of γ-ray backgrounds. All these advances, together with a better understanding of the requirements for siting of neutron detectors, has led to the belief that in any reactor type the neutron flux can now be measured from shut-down to full power. This being so, it has now been accepted as a part of reactor control philosophy that the neutron flux and its rate of growth or decay should be displayed to the operator at all times.

Advances in the electronic-circuit techniques have led to the development of a system of instrumentation that presents the neutron-flux data in a form convenient to the operator. It is felt that, although there might be developments in the circuit techniques of individual units, the system of instrumentation is likely to remain for some time to come, because of its convenience to the operator.

(9.1) Logarithmic Power-Level Indicators and Period Meters

It is a characteristic of reactors that, when they are supercritical and below power levels where temperature effects are important, the neutron flux increases exponentially after the initial transient has died away. If the neutron flux is displayed on a meter which is calibrated logarithmically, the pointer will move across the scale at a uniform rate. Differentiating the output of this logarithmic power-level indicator will provide a signal which gives a measure of the rate at which this needle is moving and can be presented on a meter calibrated in reactor period or doubling time. This signal can also be used to shut down the reactor should the period be excessively short. This instrument has been called a reactor-period meter; it gives the operator an indication of the rate at which the reactor is diverging and gives him an at-a-glance indication of the reactor power. The instrument is therefore the key one during the starting-up phase and is also suitable for monitoring the reactor when it is shut down.

The d.c. versions of the reactor-period meter use the emission from a cathode operated in the retarding field region. It can be demonstrated that, because the electrons leaving the cathode have a Maxwellian velocity distribution, the voltage across a diode in the retarding field region is proportional to the logarithm of the current flowing through it. The current from

the ionization chamber is passed through the diode and the voltage across it is measured. The disadvantage of a simple diode is that the whole characteristic shifts considerably with change in cathode temperature. It has been shown that, by using the mutual characteristic between two electrodes in a multi-electrode valve, this shift can be cancelled. The most popular circuit uses a pentode.* The ionization-chamber current is passed through the grid–cathode region, producing a logarithmic characteristic between grid current and grid voltage, the screen-grid potential being adjusted by a d.c. amplifier to keep the anode current constant. Provided that the amplification factor between the control and screen grids is a constant over the range of interest, the change in screen-grid potential will be proportional to the logarithm of the grid current. With ME1400 valves (CV432) the logarithmic characteristic extends from 3×10^{-5} to about 10^{-11} amp, and with ME1403 (CV2348) valves the range is from 3×10^{-7} to 10^{-13} amp. A current of 10^{-4} amp would appear to be the upper limit for any practical valve, but it should be possible to combine this with a lower limit of 10^{-12} amp.

Pulse-counting instruments are used with logarithmically calibrated scales, using the counting-rate-meter system described by Cooke-Yarborough and Pulsford.[6] Because of the poor statistical accuracy of pulse-counting apparatus, a period meter attached to such a system has a limited usefulness for an operator. It is, however, quite suitable for providing a period-meter 'trip', provided that this is set to a period not longer than about 10 sec.

Reactor-period meters are used up to powers where the reactor temperature coefficient becomes significant. Above this limit, of course, the reactor divergence ceases to be exponential for small values of K_{ex} (see Fig. 5) and they therefore lose their usefulness to the operator.

In some reactors the full range of fluxes can be covered by one period meter (e.g. those using heavy water as a moderator), but more generally two meters are necessary: that covering the lower-flux end of the range may need to be a pulse-counting system, but a d.c. system is to be preferred if it is at all feasible.

(9.2) Linear D.C. Amplifiers

When the neutron power of the reactor has reached the normal operating levels, the operator's attention is diverted to the linearly calibrated power-meters—almost universally high-gain feedback d.c. amplifiers. They may use valves throughout in a direct-coupled system, but there are advantages in using synchronous-convertor types of amplifier; these have a better zero stability, so that wire-wound resistors can be used as the feedback resistors for the lower-current ranges, giving better long-term stability, and if recording of the power is required, the overall system can be simpler.

For the second-to-second control of the reactor it is convenient to present on a meter the difference between the desired power level and the actual power level. The desired power level can include a signal computed from the thermal state of the reactor and becomes the primary quantity for the reactor control when at power. It is usually supplemented by a linear-scale instrument with decade range switches. This instrument presents the total neutron power and is used as a cross-check on the 'backed-off' instrument. This switching is generally incorporated only if it is intended to operate the plant at fractional powers for appreciable periods, i.e. it applies most generally to research plants.

(9.3) Shut-Down Amplifiers

Shut-down amplifiers either release the control elements or reduce reactivity at a controlled rate should the neutron flux exceed some predetermined level. The safety mechanism generally use magnets to hold up the rods, so that interrupti the magnet current releases the rods. A system is therefo needed which can measure the reactor power and then redu the current in the magnet by a large amount for a small increa in reactor power, i.e. some form of non-linear element is neede Moreover, the equipment, should it fail, should give an indicati that it is incapable of operating when called upon again. A sat factory way of doing this is to arrange that the system gives indication of excessive neutron flux when it fails. This has be called 'failure to safety'. In the past a popular form of circuit h been the Schmidt trigger circuit, in which the valve normally co ducting holds a relay in the energized state and the other valv the input valve, is cut off. Excessive neutron flux should tu on the input valve and cut off the valve with the relay in circuit. However, in the normal state there is no way of ensuri that the input valve can, in fact, be turned on when required, that the other valve can be turned off.

Much attention has been given recently to systems which ha a higher probability of failure to safety. One system uses high-gain direct-coupled amplifier: in the normal state its amp fying valves are neither conducting fully nor cut off, and two them have relays in their anode circuits which are normal energized with their contacts connected in series. When the is an excessive neutron flux, a biased diode connected to the ou put conducts, removing the feedback, so that a small increase neutron flux cuts off one of the valves and de-energizes its rela Some catastrophic faults would cause a large output signal in t same direction with the same result; other faults could cause large output signal in the opposite direction, causing anoth diode to conduct and de-energizing the other relay. In anoth system, the ion-chamber current flows through an earthe resistor, producing a p.d. across it proportional to the react power. A synchronous convertor examines alternately this p. and an adjustable trip-setting voltage. The signal on the movi contact of the synchronous convertor is therefore a square wa with an amplitude equal to the p.d., and it is applied to the inp of an a.c. amplifier whose output is connected to a phas sensitive detector. The reference signal of this detector is t same as that on the driving coil of the synchronous converto and its output is fed to a polarized relay, which is therefo normally energized. When the voltage across the input resist is equal to the trip setting, there is no input to the a.c. amplifi and the relay will become de-energized. When the voltage acro the input resistor exceeds the trip setting the current through t relay coil reverses in sign, holding the armature more firmly the de-energized side. There is therefore a signal flowing throu the amplifier in the safe-neutron-flux condition. Any fault whic interrupts this signal produces a trip action immediately, a any fault which reduces its size merely causes the trip action occur at a neutron flux lower than the trip setting.

These improvements have made the reactor safer, but at t expense of making it more prone to accidental shut-down due equipment failure. By using three equipments connected so th two of them must operate to produce a shut-down, and o operating alone will produce merely a warning, the reliability the system is considerably improved without affecting its safe

(9.4) Ion-Chamber H.V. Supplies

With mean-current ionization-chamber systems, a failure in t polarizing-voltage supply or in the connection to the chamb could lead to a dangerous situation. For example, while t reactor is shut down during maintenance the connecting le may become disconnected. At low powers the instrume channel could appear to be in a satisfactory operating conditic because the contact potential between the chamber electrodes m

* British Patent Application No. 16929, 1953 and corresponding U.S. patent application.

sufficient to saturate the chamber; at high powers it would be ite inadequate. The danger is guarded against by providing o leads to the polarizing electrode, one connected to the voltage pply and a separate voltage-measuring lead connected back to e control room. A voltmeter, or simple form of electronic lay, gives an indication that both leads are intact and that the d. is adequate. The reactor-period meter, because it has a fferentiating circuit, is quite sensitive to fluctuations in the larizing voltage to its ion chamber. A power supply run from e mains would need to be of the degenerative-feedback type th quite a high loop gain with a reference supply free of noise. Britain it is preferred to use batteries for the polarizing voltage, cause they provide the required freedom from fluctuations and aintain the voltage after a mains supply failure, thus allowing e reactor power to be measured on a simple moving-coil icroammeter.

(10) CONCLUSION

The paper has reviewed broadly some of the basic nuclear-ysical principles affecting reactor control and instrumentation, ustrating the arguments by reference to practical reactors erever possible.

Much experimental and theoretical work remains to be done especially in connection with the overall power-station control problem, and it is felt that possibly the most useful service rendered in this presentation is to show where some of the major problems lie, to explain the approaches adopted to date, and to give a guide to new or future reactor control design.

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[The discussion on the above paper will be found on page 607.]

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Paper No. 2029
Mar. 1

NUCLEAR-REACTOR-CONTROL IONIZATION CHAMBERS

By W. ABSON, B.Sc., Associate Member, and F. WADE, Associate.

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SUMMARY

The paper describes the design and the electrical characteristics of a neutron-sensitive d.c. ionization chamber suitable for a wide range of applications in nuclear-reactor-control instrumentation systems. Thermal-neutron sensitivities of 10^{-15}–10^{-14} amp/n/cm^2/sec can be obtained using boron trifluoride filling or boron-coated electrodes with hydrogen filling. The corresponding γ-radiation sensitivities are of the order of 10^{-12}–10^{-11} amp/r/h. Virtually complete collection of the ionization current is possible, up to neutron flux levels of 10^{11} n/cm^2/sec, with a polarizing voltage of a few hundred volts. The residual current due to neutron-induced activities in the chamber falls to less than 10^{-6} times the full-power neutron current some 20 min after shut-down.

The siting of ionization chambers has an important bearing on their range of utilization in control-instrumentation systems, and this is discussed briefly in relation to the electrical characteristics of the chambers described.

LIST OF SYMBOLS

S_n = Neutron sensitivity, amp/n/cm^2/sec.
S_γ = γ-radiation sensitivity, amp/r/h.
V' = Inter-electrode voltage for 90% ionization-collection efficiency.
I = Current, amp.
I_s = Saturation current, amp.
I_R/I_N = Ratio of residual current to neutron current in an ionization chamber.
N = Full-power neutron flux, n/cm^2/sec.

(1) INTRODUCTION

Neutron-flux measuring equipment is used in nuclear-reactor instrumentation systems to provide a measure of reactor power for control during starting-up, for control at a steady operating level and for the operation of shut-down controls at a preset power level. The neutron detectors are usually placed outside the reactor core but within the surrounding radiation shielding structure, and the neutron flux at these points may not bear a constant relation to the total power output. In large power-producing reactors, control at full power will also involve the measurement of many other parameters, such as heat output, coolant temperatures, etc., which may be used to correct for long-term changes in the ratio of neutron flux to power level and for changing the trip-level of the safety shut-down mechanisms. Neutron-flux measurements provide a convenient method for short-period control at a constant power level and for the rapid operation of the safety mechanisms in the event of sudden transients. They are also necessary for complete control at sub-critical level and during starting-up. The response of the neutron detectors to γ- and β-radiations from the core fission products and other induced activities in the detector or surrounding structures must be negligible compared with their response to the neutron flux over the required range of measurement. The necessary discrimination may be achieved by the use of a pulse-type detector, such as a fission counter, in which amplitu discrimination is used to differentiate between neutron and γ- pulses, and the individual neutron pulses are counted in a count rate-meter. In many reactor instrumentation applications i possible to achieve a sufficient degree of differentiation betw neutron and γ-ray flux by the use of a simple 2-electrode ioni tion chamber filled with boron trifluoride or with boron-coa electrodes. The ionization produced by the α-particles a lithium nuclei, resulting from the (n, α) reaction with boron is collected and measured by a d.c. amplifier. The main char teristics of the neutron detectors and the associated electro equipment used in pulse counting systems and d.c. systems U.K.A.E.A. reactors have been described by Cox, Gillespie a Abson.[1] A d.c. ionization chamber system is to be preferred t pulse counting system because of its greater simplicity, reliabi and flexibility.

The new ionization chambers to be described have b developed for use in some of the new experimental reactors A.E.R.E. and for use in the U.K.A.E.A. power reactors. T design is based on that of the type T.Q.T. chamber[2] which been in use for several years in U.K.A.E.A. reactors. T overall size of the chambers, 3½ in diameter and about 8 in lo has proved to be a useful practical compromise between sensiti and convenience of use in a variety of types of reactor. T inherent neutron/γ-radiation sensitivity has been reduced to lowest practicable limit possible in a 2-electrode chamber, a the effects of long-term residual activity have been reduced b factor of seven below those in the earlier T.Q.T. design. T effect of variations in electrode coating and gas filling on neutron and γ-radiation characteristics have been investigat and the results are discussed in relation to different applicatio in nuclear reactors.

(2) DESIGN AND CONSTRUCTION

Fig. 1 shows a section of the new ionization chamber (t RC/1). The electrode spacing is 6·2 mm, and the coatable a is approximately 500 cm^2, 280 cm^2 on the inner surface of outer electrode and 220 cm^2 on the outer surface of the in electrode. When used with a boron-trifluoride gas filling sensitive volume between the electrodes is 180 cm^3. A simi design (type RC/2) with shorter electrodes, having a coata area of 200 cm^2 and a sensitive volume of 100 cm^3, has also b developed.

The electrodes and the cylindrical part of the outer case are sp from aluminium sheet (99·8% aluminium to B.S. 1470/S1A the electrode thickness being 0·020 in, and the thickness of outer case 0·064 in. Each electrode is mounted rigidly from base-plate on an insulated terminal; these lead-through termin are sealed by thin lead washers (0·003 in) held in compressi against quartz insulators by means of a high-tensile-steel b The design is based on that used originally by Carmicha The insulator is assembled and processed so that the area of lead washer in contact with the quartz and steel faces of insulator components is in a compressive stress of approximat 6 000 lb/in^2. Insulation resistances in excess of 10^{15} ohms can obtained if the quartz insulators are degreased and cleaned a

Mr. Abson and Mr. Wade are at the U.K.A.E.A. Atomic Energy Research Establishment.

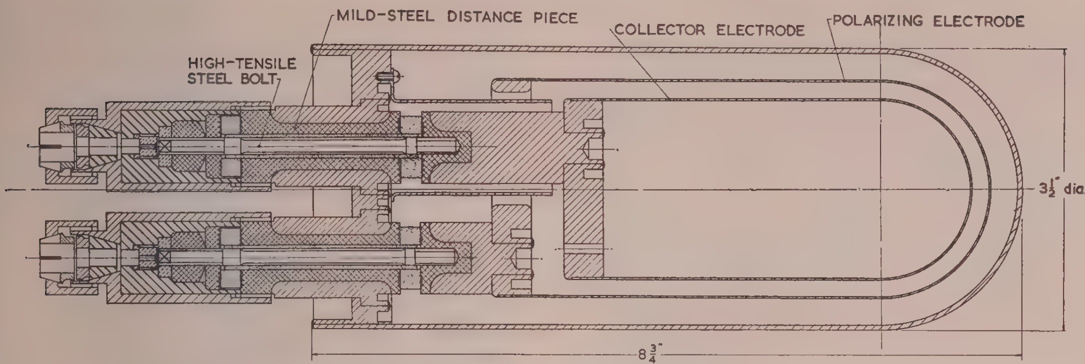


Fig. 1.—Type RC/1 ionization chamber.

- Aluminium 99·8%.
- Phosphor bronze.
- Polythene.
- Steel.
- Quartz.

are is taken during assembly to avoid any further contamination f the surfaces. The steel distance piece is shrouded in aluinium by means of the Al–Fin process, and this component ay then be welded into the chamber base-plate as shown in ig. 1. By the use of the Al–Fin technique it has been possible arrange for all the lead-gasket seals to be made between uartz and mild-steel surfaces. It has also been possible in the ew design to reduce considerably the total amount of highnsile steel used in the terminal compared with earlier designs, d furthermore, to arrange that no β-radiation from activated eel parts can contribute to the ionization-chamber current.

Fig. 2 shows the method used for connecting a flexible polyene-insulated concentric cable to the collector electrode terinal. For applications where a low residual current is cessary, e.g. in reactor starting-up measurements, it is important avoid collection of ionization from free-air spaces round the llector lead or terminal connection, and polythene packing eces are used to limit these spaces. A similar method of nnection may be used for the polarizing-electrode lead, but it preferable here to use a 2-wire screened lead. One of the wires used to connect the h.t. supply to the polarizing-electrode rminal, and the other is connected to a voltmeter mounted in e control room. This is a convenient method of ensuring at the h.t. supply connection has been made and that the larizing voltage is adequate.

Boron coatings approximately 1 mg/cm^2 thick are applied to e electrodes by spraying or painting with a liquid dispersion of wdered boron; these are subsequently baked at 200–300° C. or natural boron coatings, amorphous boron in Formvar* lutions have been used. More recently, boron coatings have en produced using a finely divided dispersion of crystalline ron in white spirit. The resistance of these boron coatings is proximately 10^7 ohms/cm^2, and this is satisfactory for coated eas of several hundred square centimetres and ionization rrents up to 10^{-4} amp. The resistance of the coatings can, wever, be reduced to about 10^5 ohms/cm^2 by the addition of a w per cent of powdered graphite to the powdered boron.

ELECTRICAL CHARACTERISTICS OF RC/1 AND RC/2 TYPE IONIZATION CHAMBERS

(3.1) Neutron and γ-Radiation Sensitivities

The neutron and γ-radiation sensitivities for ionization ambers with various electrode coatings and gas fillings are given in Tables 1 and 2, and the effect of variation of the hydrogen pressure in the case of boron-coated chambers is shown in Fig. 3.

* Polyvinyl formal in ethylene dichloride.

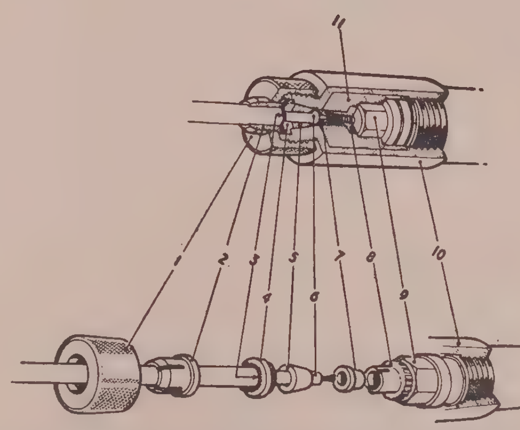


Fig. 2.—Cable connection for ionization chamber.

1. Knurled clamping nut.
2. Aluminium cable clamp.
3. Copper braid.
4. Aluminium clamping washer.
5. Polythene compression plug.
6. Polythene cable insulator.
7. Plug.
8. Socket.
9. Insulator nut.
10. Outer case.
11. Polythene packing piece.

The neutron sensitivity figures, S_n, were obtained from measurements with ionization chambers placed in the graphite

Table 1

Neutron and γ-Radiation Sensitivities for 1 mg/cm^2 Coatings of Natural Boron, 6·2 mm Electrode Spacing and Hydrogen Gas Filling

Ionization chamber type	Area of boron coating	Hydrogen pressure	S_n	S_γ	n/cm^2/sec equivalent to 1 r/h
	cm^2	cm Hg	amp/n/cm^2/sec	amp/r/h	
RC/1	500	150	6×10^{-15}	6×10^{-12}	$1{\cdot}0 \times 10^3$
		15	$1{\cdot}5 \times 10^{-15}$	6×10^{-13}	$4{\cdot}0 \times 10^2$
RC/2	200	150	$2{\cdot}4 \times 10^{-15}$	$3{\cdot}3 \times 10^{-12}$	$1{\cdot}4 \times 10^3$
		15	$0{\cdot}6 \times 10^{-15}$	$3{\cdot}3 \times 10^{-13}$	$5{\cdot}5 \times 10^2$

Table 2

NEUTRON AND γ-RADIATION SENSITIVITIES FOR BORON-TRIFLUORIDE FILLINGS (BORON ENRICHED TO 96% BORON 10)

Ionization chamber type	Sensitive volume	$B^{10}F_3$ gas pressure	S_n	S_γ	n/cm²/sec equivalent to 1 r/h
	cm³	cm Hg	amp/n/cm²/sec	amp/r/h	
RC/1	180	30	$2 \cdot 9 \times 10^{-14}$	$1 \cdot 35 \times 10^{-11}$	$4 \cdot 6 \times 10^{2}$
RC/2	100	30	$1 \cdot 6 \times 10^{-14}$	$0 \cdot 75 \times 10^{-11}$	$4 \cdot 6 \times 10^{2}$

Note:—S_n for chambers filled with natural boron trifluoride is approximately one-fifth of the values quoted above.

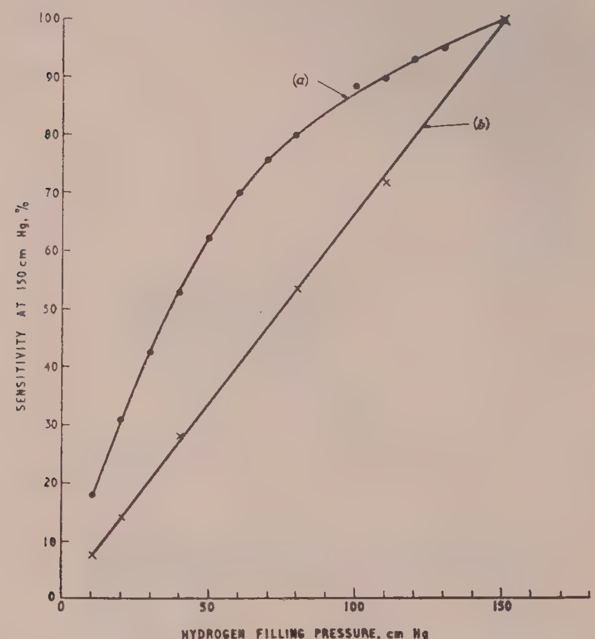


Fig. 3.—Variation of neutron and γ-radiation sensitivities with hydrogen pressure, for type RC/1 chamber with boron-coated electrodes and 6·2 mm electrode spacing.

(a) Neutron sensitivity.
(b) γ-radiation sensitivity.

thermal column of Bepo (British experimental pile). Values for the neutron flux at the chamber position were obtained by activation measurements with both manganese foils and cobalt wires. In each case, foils or wires were placed on the hemispherical nose and the base-plate of the chamber, so that a correction could be applied for the flux gradient in the thermal column, and the sensitivities quoted apply for the estimated neutron flux at the centre of the sensitive portion of the chamber. For the measurements with manganese foils the chamber was exposed in a flux of the order of 10^7 n/cm²/sec for about 10 min and the β-activity of the foils was subsequently measured using an end-window Geiger–Müller counter. When cobalt wires were used the chambers were exposed for several days at a flux level of the order of 10^{10} n/cm²/sec, and the induced activity was then measured by both β- and γ-radiation measurements. The agreement obtained between the two methods, for the same value of S_n, was about 15%, and the values given are the average of the two measurements. The activation measurements were made with one ionization chamber (a boron-coated type), and this was then used as a standard for subsequent measurements of the neutron sensitivity of chambers with different coatings and gas fillings. The γ-sensitivity measurements were made using a radium source. The value of S_γ will depend on the energy the γ-radiation, since the chamber is made of aluminium a not of 'air equivalent' material, but this effect is not importa for energies greater than about 0·3 MeV, and the figures quo are adequate for most calculations arising in the use of ionizati chambers in reactor-instrumentation systems.

The α-particle released in the reaction between boron 10 an neutron has a range of about 0·5 mg/cm² in boron, and neutron sensitivity[4] of a boron-coated chamber falls by ab 20% if the thickness is reduced to 0·2 mg/cm². Coatings 1 mg/cm² have been used in the new chambers because coating process becomes more difficult for thinner layers. T neutron absorption in a 1 mg/cm² layer is only about 5%, a there is thus no real disadvantage in using a thickness somewh greater than that necessary to obtain maximum sensitivity. F enriched-boron coatings this will not apply and it will be pref able to use thinner coatings. Hydrogen is used as the filling g since this gives the lowest γ-radiation sensitivity for a giv neutron sensitivity.* With a 6·2 mm electrode spacing, abo 90% of the maximum possible sensitivity is obtained with hydrogen pressure of 150 cm Hg. By reducing the hydrog pressure the ratio of neutron to γ-radiation sensitivity can increased at the expense of a reduced neutron sensitivity, but main advantage to be gained by using lower-pressure fillings an improvement in ionization collection characteristics.

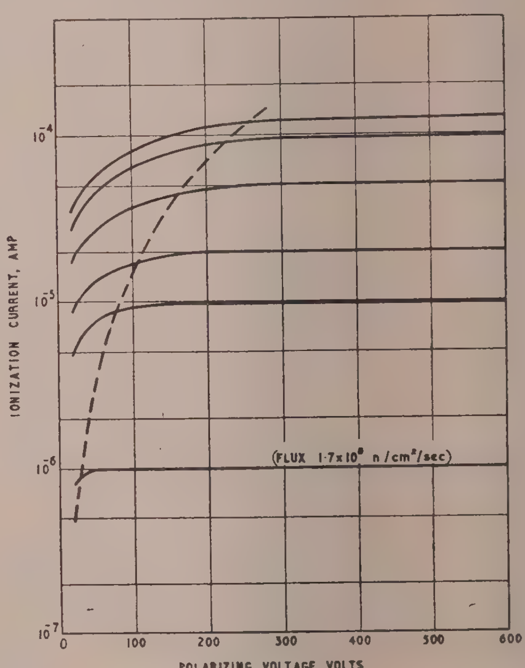


Fig. 4.—Saturation characteristics of RC/1 chamber with both electrodes boron coated and hydrogen filled to 150 cm Hg.
---- V' for 90% collection efficiency.

(3.2) Ionization Collection Characteristics

Fig. 4 shows a family of curves relating collected ionizati current at a number of flux levels with the polarizing volta applied between the electrodes, for a boron-coated type

* The γ-radiation sensitivity of the ionization chamber is determined mainly by mass of gas per unit area between the electrodes and will be approximately the s for a given mass of any gas. The mass of gas required to achieve a given neut sensitivity decreases as the atomic weight of the gas decreases. For example, RC/1 chamber filled with argon at a pressure of 45 cm Hg would have the same neut sensitivity as a chamber filled with hydrogen at 150 cm Hg, but the γ-radiation se tivity would be about six times greater.

onization chamber. V' is a useful criterion for assessing the olarizing voltage required for particular applications; in general, he collection is more than 99% complete at an applied voltage of $2V'$ and is virtually complete at $4V'$. Table 3 gives further

Table 3

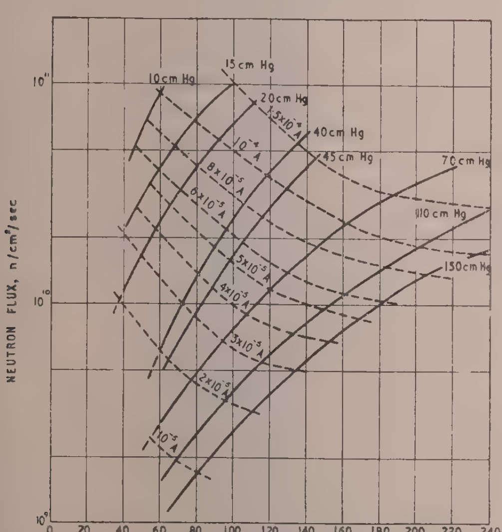
Collection Characteristics of RC/1 Ionization Chamber

Polarizing voltage	Ionization collection ($I/I_s \times 100$)	Change in collection for 10% change in V
	%	%
V'	90	
$2V'$	99·3	0·15
$3V'$	99·8	<0·10
$4V'$	100	<0·05

Electrodes coated with natural boron 1 mg/cm² thick.
Hydrogen pressure = 150 cm Hg.
Saturation current at 10^{10} n/cm²/sec = 6×10^{-5} amp.
Voltage for 90% ionization collection = 180 volts.

letails of the collection characteristics for applied voltages greater than V' for a boron-coated and hydrogen-filled chamber.

The ionization collection efficiency is increased by a reduction n gas pressure, since the ionization density is reduced and the peed of collection of ions is increased. Fig. 5 shows a family of urves of V' against neutron flux at various gas pressures. The ensitivity of the chamber changes with gas pressure, and the aturation currents collected at the different gas pressures are lso indicated in Fig. 5. The results on ionization collection



ig. 5.—Effect of hydrogen pressure on collection characteristics of RC/1 chamber, with both electrodes boron coated.

—— V'/neutron flux.
----- Lines of constant ionization current.

iven above were obtained from measurements with natural-oron coatings; they will apply to enriched-boron coatings if llowance is made for the fact that a given ionization current .e. a given ionization density) will be obtained at a lower eutron flux.

In order to obtain the best possible saturation characteristics, he boron coatings are restricted to those parts of the electrodes where there is a uniform electric field, i.e. over the region of the hemispherical ends and over the cylindrical surfaces to within about 6 mm of the plane supported ends. If only one electrode is coated with boron there is an advantage in making this the negative electrode. Ionization is most dense near the coated electrode, and the positive ions are thus collected more quickly when this electrode is negatively polarized. V' is some 10–20% less in this case than in the case of a positively polarized coated electrode. The collection characteristics are affected by the temperature at which the ionization chamber is operated: V' is increased by about 30% when the operating temperature is increased from 20 to 80° C for a boron-coated chamber with 150 cm Hg pressure of hydrogen in a neutron flux of about 10^{10} n/cm²/sec (60 μA ionization current). The neutron and γ-radiation sensitivities are not affected by this temperature change, since the mass of gas between the electrodes remains constant.

Fig. 6 shows ionization-collection/polarizing-voltage charac-

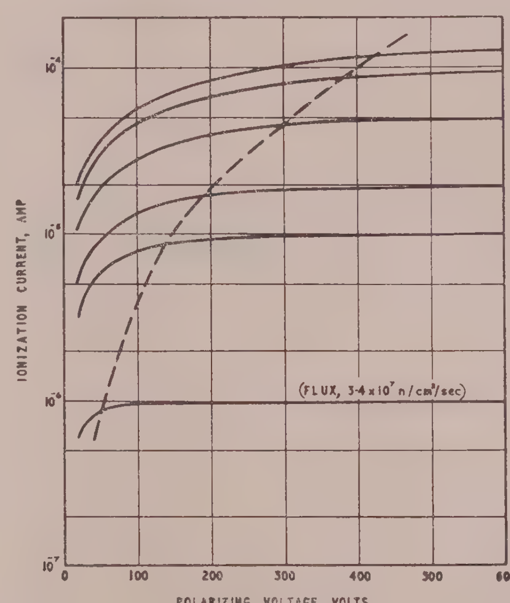


Fig. 6.—Saturation characteristics of RC/1 chamber filled with boron trifluoride (96% enriched in boron 10) at 30 cm Hg.

---- V' for 90% collection efficiency.

teristics for an RC/1 chamber filled with boron trifluoride enriched to 96% boron 10. The results apply also to a natural boron-trifluoride gas filling if the neutron-flux values are increased by a factor of five. It will be noted that the value of V' for a given ionization current is about 1·8 times that required with a boron-coated chamber filled with hydrogen to 150 cm Hg. Most of this reduction in collection efficiency is due to the differences in collection properties of the two gases, but it is partially due to less-efficient collection in the region of the supported ends of the electrodes. Boron coatings are deliberately restricted so as not to produce ionization in these regions. It is of interest to note that the use of a guard-ring electrode over the collector-electrode supporting terminal has considerably improved the collection efficiency of boron-trifluoride-filled RC/1-type chambers over that of the T.Q.T. design. The latter had no guard-ring electrode, and there was a correspondingly larger sensitive volume in the region of the electrode supports over which the electric field was considerably less than that between the cylindrical surfaces of the electrodes.

(3.3) Residual Activity Currents

The main activity induced in the RC/1-type ionization chamber during neutron irradiation is aluminium 28 (2·4 min half-life). When the neutron flux is removed the ionization current due to this activity (3·0 MeV β-rays and 1·8 MeV γ-rays) falls with a decay-time characteristic of the aluminium 28, until the effect of other longer-lived activities becomes comparable with that of the aluminium. The exact nature of the decay curve will depend on the previous irradiation history of the chamber, and Fig. 7 shows results obtained with a boron-coated chamber which had been irradiated in the Bepo thermal column (at a neutron-flux of about 2×10^{10} n/cm²/sec) for 12 weeks. The current decay is characteristic of aluminium for about 20 min after removal from the neutron flux, and the subsequent current is due to impurities in the aluminium electrodes and the outer case (manganese, copper and zinc) and to manganese, copper, zinc, iron, nickel, cobalt and molybdenum in the lead-through terminals and cable connections. The greater part of this longer-term residual current is due to the electrodes and the outer case, since β-activities in these components can produce ionization in the sensitive volume of the chamber. Separate measurements with a demountable air-filled chamber containing no boron coating indicated that up to periods of a few hours after shut-down the terminals and cable connections contributed less than 25% of the total residual ionization current. The residual current at 30 min after shut-down is about 0·15 of that obtainable with the T.Q.T. design. The improvement is due to the new design of the electrode support terminal (i.e. the reduction in the amount of steel and the use of an additional guard-ring electrode), and to the use of a higher-purity aluminium (99·8% instead of 99%). The ratio I_R/I_N for various types of chamber fillings may be estimated

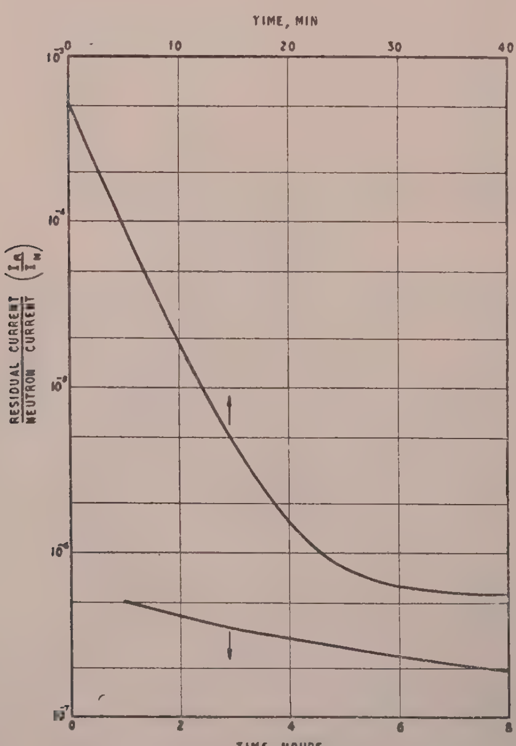


Fig. 7.—Residual activity current following removal from neutron flux, for RC/1 chamber with both electrodes boron coated and hydrogen filled at 150 cm Hg.

Table 4

Electrode coating	Gas filling	I_R/I_N 30 min after shut-down	I_R/I_N 8 h after shut-down
		$\times 10^{-6}$	$\times 10^{-6}$
Natural boron	H_2, 150 cm Hg	0·65	0·2
(500 mg)	H_2, 15 cm Hg	0·26	0·08
None	$B^{10}F_3$, 30 cm Hg	0·3	0·095

from the results given in Fig. 7 if the relative neutron an[d] γ-radiation sensitivities are known.* Table 4 gives values [of] I_R/I_N at 30 min and 8 h after a shut-down for boron-coated an[d] boron-trifluoride-filled chambers of the RC/1 size.

(4) RANGE OF UTILIZATION: THE SITING OF IONIZATIO[N] CHAMBERS

(4.1) High-Power-Level Application

A high degree of stability is required in the neutron-flu[x] measuring channel used for the steady control of a reactor at fu[ll] power. The ionization-chamber sensitivity should be as high [as] is consistent with an adequate ionization collection efficienc[y] and boron-coated chambers are to be preferred if the neutro[n] flux level exceeds about 10^9 n/cm²/sec, because of their superi[or] ionization collection characteristics. It is advisable to arran[ge] that the chamber operates at a point on the saturation chara[c]teristic where the polarizing voltage is at least $3V'$, i.e. the ioniz[a]tion collection is complete within a small fraction of 1%, an[d] the stability is better than 0·1% for a 10% change in th[e] polarizing voltage (see Table 4). For example, if the chamber [is] required to operate at neutron-flux levels up to 10^{11} n/cm²/s[ec] and the polarizing voltage available is 300 volts, it will be nece[s]sary to use a hydrogen pressure of 15 cm Hg (for a natural-boro[n] coating on the electrodes) in order to meet this specificati[on] ($3V' = 300$ volts).

A less-stringent specification will often be satisfactory f[or] ionization chambers used for the operation of shut-down contro[l] at a preset power level or at a preset level of reactor period [or] doubling time.† For example, a collection efficiency of abo[ut] 98% at the lowest permissible polarizing voltage will usually [be] adequate.

(4.2) Wide-Range Ionization Chambers

For the higher-power-level applications discussed in Section 4[.1] it is not usually difficult to site the ionization chambers so th[at] the current due to β- or γ-radiation is small compared with th[at] due to the neutron flux. The problem becomes more difficu[lt] when ionization chambers are required for control during sta[rt]ing-up from a sub-critical level, and special measures are usua[lly] necessary to obtain the required ratio of neutron flux to γ-radi[a]tion dose rate at the ionization-chamber position. The soluti[on] will depend on the type and size of the reactor, but the gene[ral] principles will be the same, i.e. the use of moderating mater[ial] around the ionization chamber to enhance the thermal-neutr[on] flux, the use of lead shielding to reduce external γ-radiation a[nd] the use of neutron sources in the reactor to increase the su[b]critical neutron flux.

In a large graphite-moderated reactor a 'thermal column' co[n]sisting of a block of graphite forming, in effect, an extension [of] the graphite in the core may be used to increase the therm[al]

* It is assumed that the ionization current produced by the chamber activities va[ries] with the gas filling in the same way as the γ-radiation sensitivity.

† The ionization chamber current is measured in a logarithmic d.c. amplifier [and] the output voltage is differentiated, giving a signal inversely proportional to the reac[tor] period.

neutron flux. This graphite block will itself attenuate the γ-radiation from the core fission products. Any lead which is used for additional shielding should be placed immediately around the chamber and should be of high purity to avoid further unwanted induced activities.

The range of use of neutron sources in different types of reactor to increase the sub-critical neutron flux is outside the scope of this paper, but is discussed in the paper by Cox and Walker.[7] In a large graphite-moderated reactor a sub-critical power of 10^{-8}–10^{-7} of the full-power level is feasible. Thus, for the current due to external γ-activity in an RC/1 ionization chamber (boron-coated and hydrogen-filled to 150 cm Hg) to be equal to the neutron current at a flux 10^{-8} times the full-power level, it would be necessary for the γ-radiation level to be reduced to

$$\frac{10^{-8} \times N \times 6 \times 10^{-15}}{6 \times 10^{-12}} = N \times 10^{-11}\,\text{r/h}$$

It is also necessary to consider the residual currents due to induced activity in the ionization chamber. It will be seen from Table 4 that the RC/1 chambers will be limited by these effects to a range of about 6–7 decades, for starting-up measurements between 30 min and 8 hours after a shut-down. If, however, two separate measuring channels are used for starting-up equipment, one of the ionization chambers may be retracted from its starting-up position once the reactor has been brought up to full power. The retracted position should be chosen so that the activities induced in the chamber are negligible compared with the current due to the sub-critical neutron flux at the starting-up position. In this way, eight decades of power level could be covered with an overlap of several decades between the two channels.

In addition to the problems of differentiation between neutron flux and γ- and β-radiation, the lower level of neutron-flux measurement will also depend on the chamber sensitivity and on the statistical fluctuations in the ionization current. The lower level of current which can be measured conveniently and reliably in both linear and logarithmic d.c. amplifiers used in reactor instrumentation installations is about 10^{-12} amp. This corresponds to a neutron flux of about 170 n/cm^2/sec for a RC/1 ionization chamber with the electrodes coated with natural boron and a hydrogen pressure of 150 cm Hg, or about 40 n/cm^2/sec for a highly enriched coating. For a chamber filled with highly enriched boron trifluoride at 30 cm Hg, the figure is 35 n/cm^2/sec. An approximate estimate of the statistical fluctuations in the ionization current in such a chamber can be made in terms of the total absorption cross-section of the gas between the electrodes. For a sensitive volume of 180 cm^3 (RC/1 size) and a gas pressure of 30 cm Hg, the mass of boron 10 is 0·032 g, and the thermal-neutron absorption cross-section is 7·0 cm^2. The average number of ionizing events per second for unit neutron flux is therefore 7. The ionization current at a flux of 35 n/cm^2/sec is 10^{-12} amp, and if this is measured with a linear d.c. amplifier system having a time-constant of 1 sec, the relative standard deviation in the output will be about 5%. An ionization chamber with an enriched boron coating will give a standard deviation of the same order of magnitude at the same flux level.

(4.3) Calibration Adjustment

The calibration of the output of ionization-chamber measuring channels in terms of reactor power is usually carried out periodically by comparison with heat-output measurements. The relation between neutron flux at the ionization-chamber position and reactor power will vary with core-loading conditions and will be affected by changes in temperature distribution with power level and by poisoning phenomena. The output meters or chart recorders and the trip settings of safety controls will be calibrated in terms of reactor power, and it will be necessary to make adjustments to offset the calibration changes mentioned above. While these adjustments may be made electrically, it is an advantage in some applications to be able to move the ionization chamber to a position of higher or lower flux, as required. The provision of adjustable chamber positions has other advantages. The calculation of neutron flux at proposed ionization-chamber positions in a new design of reactor may be subject to uncertainties of a factor of two or more, and the limits of uncertainty are most conveniently allowed for by having an adjustable chamber position. Although the RC/1 ionization-chamber sensitivity can be altered by variations in the gas filling or boron coating, this does not provide a convenient continuous adjustment; furthermore, other conditions such as ionization collection specifications may define the type of filling to be used. The RC/2 type of chamber has been developed for applications where there is a steep gradient in neutron flux at the chamber position. The electrode system in this chamber is only one-half the length of the RC/1 size (6·5 instead of 13 cm) and it is therefore possible to make more effective use of the change in neutron flux in a short thermal column.

(4.4) Radiation Damage Effects

T.Q.T.-type ionization chambers have been subjected to life tests in the centre of Bepo and have operated satisfactorily after several months' irradiation;[2] the neutron flux was about 10^{12} n/cm^2/sec and the γ-radiation level about 10^6 r/h. The RC/1 type of chamber is basically of the same construction and should therefore have several years' life in neutron flux levels as high as 10^{11} n/cm^2/sec and γ-radiation dose-rates of up to 10^5 r/h. A neutron-flux level of 10^{11} n/cm^2/sec is also approaching the practical upper limit for obtaining adequate ionization collection efficiencies, even when low hydrogen pressures are used. The depletion of boron 10 at this flux level is also becoming appreciable (10% in about 5 years).

Radiation damage effects in polythene-insulated cables must also be considered. Polythene becomes hard and brittle after exposures of the order of 5×10^9 rads,[5] (i.e. an energy dissipation of 5×10^{11} ergs/g). The effect of thermal-neutron absorption in small samples of polythene, e.g. a cable, is usually negligible compared with that of γ-radiation and fast neutrons. In a large graphite thermal column the energy deposition in polythene will be due almost entirely to γ-radiation arising from the capture of thermal neutrons in the graphite. In this case the damage effects in polythene will be related to the thermal-neutron flux in the graphite. For example, the γ-radiation level in the top thermal column of Bepo is approximately $0{\cdot}5 \times 10^{-6}$ r/h per n/cm^2/sec,[6] and a total dose of 5×10^9 rads (in polythene) will correspond to an integrated thermal neutron exposure of $3{\cdot}6 \times 10^{19}$ n/cm^2.

The volume resistivity of polythene is not affected by these radiation exposures, but the hardening effect may terminate the useful life of the cable, since it may lead to fracture if the ionization chamber is moved. It is preferable to use cables with an outer covering of polythene rather than polyvinyl chloride, as the latter is less radiation resistant than polythene and becomes soft and evolves hydrochloric acid.

(5) CONCLUSIONS

A fundamental problem arising in the use of d.c. ionization chambers in reactor-control instrumentation systems is the differentiation between the responses due to neutrons and γ-radiation. Some degree of compensation of external γ-radiation and of β- and γ-radiation from activities induced in a chamber can be obtained by the use of a 3-electrode system.[3,5]

It is advisable, however, to increase the inherent neutron/γ-radiation sensitivity of a 2-electrode system to the highest possible value, and to reduce induced activity effects to the lowest practicable value, before considering the further complication of an additional electrode. This has been one of the chief aims in the design of the types RC/1 and RC/2 ionization chambers. The siting of the ionization chamber, the use of γ-ray attenuating shields and the use of neutron sources in the reactor are important criteria in establishing the necessary neutron/γ-radiation discrimination and provide a more fundamental and reliable method of increasing the range of application of ionization chambers than compensation methods.

Applications may arise, however, where it is necessary to obtain some further increase in the neutron/γ-radiation response, and where the use of a compensated chamber would avoid the necessity for an additional pulse-counting instrumentation channel. A γ-compensated type of chamber incorporating the same design principles as the RC/1 chamber is being developed at A.E.R.E.

A future requirement for neutron detectors to be used for reactor control will be an ability to operate satisfactorily at higher temperatures, and it will be necessary to reconsider the design of the lead-through terminal (the type described is satisfactory to 100° C), and to replace the polythene cable connections with suitable temperature-resistant leads or cables.

(6) ACKNOWLEDGMENTS

The ionization chambers used for the measurements described in the paper were manufactured by Vacuum Industrial Applications, Ltd., and the authors wish to thank the development sta for their contributions to the mechanical design. They are al indebted to Mr. D. Young, for his assistance in the measurement The Al–Fin bonded components were supplied by Wellworth Ltd., and the boron dispersion in white spirit by Acheso Colloids, Ltd.

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[The discussion on the above paper will be found on page 607.]

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Mar. 1956

SOME DESIGN ASPECTS OF NUCLEAR-REACTOR CONTROL MECHANISMS

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SUMMARY

The paper outlines some of the practical design problems associated vith the engineering of control mechanisms in nuclear reactors. Safety is emphasized in all the design aims, and examples are given of some of the systems in use at Harwell. The scope of the paper is imited to control mechanisms for low and moderate-power experimental reactors, although some of the problems which will be met in uture power-producing reactors are mentioned.

(1) INTRODUCTION

Before the more practical aspects of nuclear-reactor control nechanisms are described, it will be helpful to look at the rather imited background of experience from which our control hilosophy has been built up. The reactors which have been uilt at Harwell, or are now being erected, cover a variety of types. They include graphite-moderated systems, heavy-water moderated ystems and fast reactors. They are all of low or moderate power utput and are, in general, entirely for experimental use. In ddition, a number of design studies have been made at Harwell n some of the possible future types of higher-output powereactors. Although no experience has yet been obtained, these tudies indicate some of the design difficulties of future control ystems within the reactor.

The overall control problem of a nuclear reactor is discussed n detail in a companion paper;* in the present paper it is proosed to discuss a more limited aspect of the subject, namely the lesign of the control mechanisms themselves.

It is well known that the steady power production in a nuclear eactor is dependent on the fissioning of the nuclear fuel at a ontinuous and steady rate, each fission releasing a number of eutrons, of which one is used to create further fission. The xcess neutrons in each generation are lost from the system by eakage, or absorbed in the various reactor materials. It is by ltering either or both these losses that control is achieved.

In thermal reactors using natural or slightly enriched uranium s fuel, materials can be inserted into the reacting core which trongly absorb thermal neutrons. Cadmium, boron and boron teel are commonly used as absorbers in this way for purposes f control.

For fast or highly enriched intermediate-type reactors the above naterials are less effective absorbers, and other methods are ecessary to enable a sufficiently wide range of control reactivity† o be built in. One method is to move some of the fuel; another s to move some of the neutron-scattering material which surounds the core; both methods alter the neutron leakage. A urther possibility is to add an absorber into a space vacated by movement of fuel. The choice of method is, however, related o the particular reactor design and the range of reactivity it is lesired to cover.

* Cox, R. J., and WALKER, J.: 'The Control of a Nuclear Reactor,' *Proceedings .E.E.*, Paper No. 2068 M, March, 1956 (103 B).

† Reactivity, ρ, is a function of the effective neutron multiplication factor, K_{eff}, the reactor, and is usually defined by

$$\rho = (K_{eff} - 1)/K_{eff}$$

Mr. Lockett is in the U.K.A.E.A. Atomic Energy Research Establishment.

The range of control reactivity built into a reactor must be such that shut-down can be achieved under every possible reasonable combination of adverse conditions and that, with certain small reservations, starting-up can also be achieved. This implies that a safe negative reactivity must be applied under shut-down conditions and that a positive reactivity can be added when it is required to make the reactor diverge. There are, however, several complications, e.g. variation of reactivity with reactor temperature, state of burn-up of fuel and fission-product poisoning. Thus, to start up a hot fuel-depleted and poisoned reactor will require appreciably more reactivity than, say, starting-up a cold reactor for the first time. It follows from this that reactivity must be added only in a manner which allows control to be safely maintained, i.e. sufficiently slowly to permit corrective action to be carried out if necessary.

(2) SAFETY PRINCIPLES

(2.1) Inherent Stability

It will already be appreciated that safe control of a nuclear-reacting system is of extreme importance and no chance of losing control must be allowed to occur; the plant designer must, however, consider this possibility. If control is lost, the reactor power will continue to rise in a manner depending on the amount of positive reactivity and the effects of self-induced reactivity changes. With a negative temperature coefficient there is an inherent stability and reactivity will fall as the temperature rises. This will set a limit to the power level which will be reached, and although this may be damaging to the reactor, effects can be localized by suitable plant design. A reactor should not be built unless it is inherently stable and will remain so under all the postulated conditions of failure.

(2.2) Operational Safety

It is clear that to maintain safe control of a reactor the method of regulation must be carefully considered in all its aspects and its reliability must be beyond doubt. Should there be any risk of losing control, shut-down should be immediate and certain. Two important reactor measurements are involved in confirming that control is being maintained within safe limits, namely power level and reactor period. If the former reaches a prearranged limiting value, or the latter becomes dangerously short, a shut-down trip must be initiated, independent of any operator.

The methods used to monitor reactor condition are explained separately in the companion paper by Cox and Walker.* It is sufficient here to state that the associated circuits end by interrupting a primary safety circuit whenever a trip is initiated. A completely fail-proof system is unlikely to be achieved in practice. This is recognized, and in order to ensure the maximum possible reactor safety, all instruments, circuits and mechanical construction should adopt the principle that any fault or failure must shut down the reactor. This fail-to-safety principle must be kept fully in mind at all stages of design. There are, of course, some items which are fundamentally unsuited to use this principle,

* *Op. cit.*

and certain types of fault which will not result in a reactor shut-down: a multiplicity of items acting in parallel then offer a solution, since coincident unsafe failure is remote.

It will be agreed that it is better to accept a number of shut-downs due to faulty tripping than to run any risk of missing a genuine trip requirement. If, however, the whole plant is over-loaded with features which may cause a shut-down trip, it may be almost impossible to start or to keep running economically. This extreme may be avoided by selective methods of accepting shut-down information in the safety-circuit design.

In addition to protection given by monitoring the reactor state, the operator must be protected from carrying out an incorrect starting-up sequence by suitable interlocking at each stage. A number of ancillary services, such as the cooling system, must be operating, access doors to hazardous positions on the reactor must be closed and all instruments must be functioning before control elements can be moved. The movement of control elements must ensure that the possible reactivity addition rate which can be applied to the system by simultaneous operation of groups of control elements is restricted to a carefully chosen maximum. In many cases the simplest way of achieving this is to permit movement of only one control group at a time and to simplify the sequence by having all other groups at one or other limits of their travel. So that the operator may continually observe the effect of his actions, not only must power level and reactor period be continuously indicated, but the movement and position of any control element must be displayed at the controlling point, together with limit-position indication.

The safety implications of servicing a control element must be taken into account; not only must it be possible to remove it without loss of control, but it should also be possible to test any unit individually in position when the reactor is shut down. A rigid interlock system must be built in to permit this single-unit testing, and safety elements must be set ready for tripping as part of the interlock requirement.

It is during sub-critical periods that the reactor condition is most uncertain and when changes may be made to the assembly which might cause an increase in reactivity through the critical state. This will give rise to a power divergence, and the reactivity changes may not be readily reversible. The normal reactivity control may already be in use, and these further safety elements are intended to provide the necessary rapid-acting reduction in reactivity.

(3) CONTROL ELEMENTS

A 'control element' is here defined as any element designed to alter the reactivity of the system. It is usually a solid element, but it could be liquid or gaseous. It may be a neutron absorber, which reduces reactivity when inserted into a reactor core; it may be a fissionable or scattering material, which increases reactivity when a reactor core is approached; or it may also be any combination of both.

A control element may be of any shape, and rods, tubes, cylinders and blades are among the many shapes in use. For this reason it seems desirable to avoid the use of the term 'rod', i.e. 'control rod' or 'shut-off rod', although these names have come into common use. In the paper the term 'control' is used in the overall sense of maintaining control over a reactor. The term 'regulating' is used where control is being exercised in a limited manner, such as maintaining or adjusting a reactor power output.

(3.1) Control Element Groups

Control elements may fall in any of the following groups:

Primary elements.
(*a*) Shut-off elements.
(*b*) Combined elements (combining shut-off and regulation).

Secondary elements.
(*c*) Safety elements.

Regulation elements.
(*d*) Coarse regulation.
(*e*) Fine regulation.
(*f*) Depletion regulation.

Standby elements.
(*g*) Loose control elements for emergency use.

Shut-off elements are designed to reduce reactivity quickl when reactor shut-down is required. When driven in th starting-up direction their speed must be limited to give a saf rate of reactivity addition, since it must be assumed that a reacto could reach the critical state while they are being moved.

Safety elements are set ready before any work, such as loadin or servicing, can be performed on a reactor. If criticality i reached through some unforeseen train of events, some contro is ready for tripping and a rapid shut-down is possible. A fusible-link method of releasing a safety element may be buil into a reactor where some additional safety device is felt to b necessary.

Regulation elements are designed to regulate a reactor by smal addition or removal of reactivity, and they are movable in eithe direction at any speed up to a chosen safe maximum. The spee in the sub-critical direction may be arranged to permit faste rates, provided that there is no possibility of this being applie in the wrong direction or undesirable temperature shocks result ing. These elements may be designed for coarse, fine or deple tion regulation. In the latter case, elements may be prevente from travelling beyond a preset position by a locked stop, whic can be reset when it is desired to add further reactivity. This i to off-set loss of fuel due to burn-up.

Combined elements are a combination of shut-off and regula tion elements, and make for economy in the total number o elements required. The combined function becomes necessar in a reactor where a large range of regulating control is require and the available space is limited. When such an element i used as a regulator the equivalent of a fast dropping speed ma be obtained by tripping the element.

Standby elements are included here for completeness, but the do not really form part of a reactor design. It is not unusual however, to have available some means of reducing reactivity b inserting a standby element in an experimental channel. This i a precautionary measure, and its existence should not be justifie by any design limitations in the regular control elements.

For shut-down purposes the primary elements control th reactor, and the amount of reactivity controlled must adequatel cover all the possibilities which lead to reactivity gain. Fo example, after a shut-down any or all of the following factors wi contribute to increase reactivity and bring the reactor conditio nearer to critical:

(*a*) Reactor cooling down.
(*b*) Fission-product poisoning diminishing.
(*c*) Removal of experimental absorbers.
(*d*) Removal of a control element for servicing.
(*e*) Addition of fissionable material in experimental channels.
(*f*) Fuel replacement.
(*g*) Possible loss of neutron-absorbing coolant.

The secondary, or safety, elements must be lifted while any c the above manual operations are being carried out, and inter locking must ensure that this is so. Therefore the safety element must not be included in assessing normal shut-down control, fo they contribute only an emergency measure of control if calle into use. To ensure that safety elements are continually teste they should fall at each trip shut-down and be raised immediatel

(3.2) Drives to Control Elements

In thermal reactors the control elements are almost invariabl absorbers which are lowered into their shut-down position fro

above. The reactor dimensions usually involve long travels between the fully-up and fully-down positions, and when it is desired to operate the reactor, absorbers must be lifted out of the reacting core without leaving any unwanted absorber behind. Wire-cable suspension is a suitable method of mechanically positioning the element and is often the only reasonable solution. The driving mechanism with this form of suspension can be situated well clear by leading the suspension cable over pulleys to wherever it is intended to site the drive unit.

In a fast reactor, absorbers have very limited effects, and for control it becomes necessary to move either core-fuel elements or scattering material surrounding the core; i.e. heavy material is lowered out of the reactor to a shut-down position beneath. Cable operation from above is still possible, but, in addition, direct operation from below is a useful alternative which is helped by the shorter travels involved in this type of reactor.

In small enriched reactors a noticeable change in reactivity can occur with lateral movement of a control element. Accurate guiding is therefore essential, but this must not prejudice a free fall when elements are tripped. To satisfy this requirement, loaded rollers have been used running on guide rails, which gives a system with no side play and enables the assembly to ride over any irregularities; no variations can occur on subsequent runs. Drive mechanisms can be mounted well below the core regions with connections made to the control elements by self-aligning drive links, or any other method which does not risk introducing any chance of sticking.

(3.3) Heat Removal

Shut-off or safety elements which are fully withdrawn during reactor operation and not designed for regulation will lie in a relatively low neutron flux outside the core region, and will not therefore require the same cooling as a regulating element, which may well be fully inserted when the reactor is at full power.

The high neutron absorption of a control element means a high rate of heat generation in the absorber material. Cooling of these items requires full consideration, and the method of construction must ensure that the control material cannot be lost by melting. It is usual to enclose the absorber in a sheath material which will satisfy both corrosion and temperature requirements.

When elements are immersed in a liquid moderator, cooling is automatic and adequate, but elements enclosed in dry re-entrant tubes will require an independent cooling system. This is not difficult if air cooling will suffice, but when liquid cooling is necessary each element must carry its own cooling channels. It is not desirable to flood the re-entrant tubes, since removal of the element during control will leave behind an unwanted absorber.

(4) CONTROL MECHANISMS

(4.1) Design Aims

The whole reactor layout is involved in the general design of a control system, for space must be shared with competing requirements, such as experimental positions, loading or fuel-change requirements, cooling features and power-measuring equipment. The importance of the control system is such, however, that design safety must not be sacrificed.

Within the high-neutron-flux regions of a reactor the structural materials are limited to those which are permissible from a nuclear standpoint. All such materials as rubber, leather, oil and organic materials will fail under neutron irradiation. The restrictions are reduced as the neutron flux diminishes, and once outside the immediate core shielding, more conventional engineering becomes possible, although further shielding may still be necessary for biological safety.

In the interests of safety there are a number of design aims to be considered, and those considered to be of overriding importance are as follow:

(*a*) The shut-down release feature should be simple and direct. When tripped the control elements should fall freely to the shut-down position.

(*b*) Gravity must always assist a shut-down and be sufficient by itself to overcome any resistance, i.e. lifting a control element must always increase reactivity and lowering a control element must always reduce reactivity.

(*c*) Any mechanical or electrical failure in a control system should bring all control elements to a shut-down position.

(*d*) The rate of reactivity addition should be strictly limited to an agreed safe value. There must be no possibility of overspeeding in the direction of reactivity increase.

(*e*) No common feature which may impair shut-down should be used; e.g. a common-trip feature would not be acceptable. There should be a separate trip feature to each mechanism or element assembly.

(*f*) Fault tripping of any one element assembly must trip the remainder. A reactor must not run with any of its elements dropped except where they are designed to do so and are adequately cooled. During a starting-up sequence, as each element is lifted it is assumed to be the one in control; if it is returned to the down position, control is assumed to be lost and a trip must occur. There is one exception to this, namely when it is desired to drop a control element deliberately to reduce reactivity more rapidly than the driving speed will do. Here the chosen action overrides what is otherwise a fault condition.

(*g*) The time required to achieve a trip shut-down must be sufficiently short to prevent any undesirable heating effects due to power or temperature overshoots. For a controlled shut-down a slow approach to the sub-critical state is preferred, in order to avoid rapid temperature changes.

There are also some features which are considered to be highly desirable and are carried out as far as practicable in any Harwell reactor; two of the more important are as follow:

(*h*) Groups of elements covering one particular function should move in parallel together. Their speed should be such that the total rate of reactivity addition will satisfy the permitted maximum. If each element had been designed for faster movement in series, it is possible to rewire the circuits so that they can operate in parallel, thus violating the maximum design rate of reactivity removal.

(*i*) At least two types of mechanism should be used in a complete control system, with a minimum of three units in each type. The amount of shut-down control available should make allowance for removal of a unit, or failure of a unit to trip.

Cable-operated elements through suitable gearing have proved to be reliable, and satisfactory design is possible if the driving motor has a defined maximum speed. A hollow threaded vertical shaft moved by a rotating drive-nut will give a direct lift. If the control element is attached by a magnet, a completely free fall is possible, and this is probably the most attractive system. Rack-and-pinion drives will also give direct lift, and the release may be achieved by a magnet carried on the rack or by a clutch on the pinion shaft. Any other direct mechanical linkage can provide a satisfactory solution, provided that the motor speed is limited.

An arrangement using a piston and cylinder is also acceptable if the seal friction can be kept low and a non-compressible fluid is used for lifting. If the control element is lifted by a compressible fluid there is no guarantee that sticking, followed by rapid motion, will not occur. This risk must not be taken.

(4.2) Positional Accuracy

The position of controls must be shown on the control desk. For a power reactor the accuracy of indication does not need to be finer than a travel corresponding to $\rho = 10^{-5}$ (an average of one-thousandth part of the travel of an element covering 1% reactivity). For experimental reactors the amount of control variation is of considerable importance in the evaluation of experimental data, and some effort must be made to give more accurate indication. The information may be shown in any

number of stages, on coarse and fine position dials, depending on the reading and accuracy required. Magslip transmitters and repeaters are normally used, and the method of indication will remain in step, since a separate transmitter is used at the control drive end for each repeater at the control desk. The error of indication between each magslip pair is usually less than 1° and, by suitable design of transmitter drive, the additional mechanical error can be kept small. Since all control elements are loaded by gravity, it is often convenient to couple the fine magslip transmitter directly to one gear shaft in the control-element drive train so that mechanical backlash error is not experienced.

(4.3) Electrical Features

Limit switches form an essential part of the operation sequence and interlock circuits. They are invariably duplicated at end limits, each switch working in a different circuit, which gives an opportunity for cross-checking circuit designs.

To obtain an accurate switch operation point in travel, micro-switches with direct plunger action are required. To avoid the risk of a switch being crushed by over-travel, a separate tilt lever is usually employed with spring loading to operate the switch. The action is still direct, but the lever moves away from the switch to operate it. A large overrun is possible with the system without endangering the switch. Fig. 1 shows a typical example.

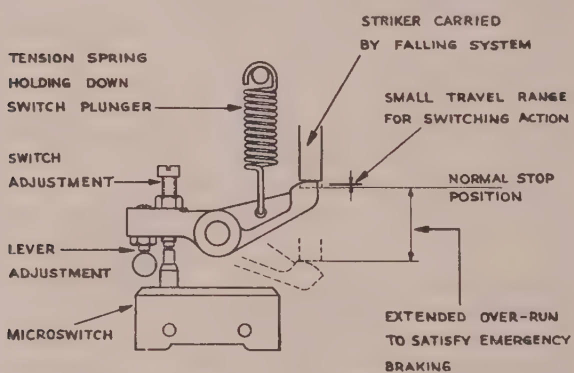


Fig. 1.—Typical operation of limit switch.

Electrical connections from switch groups are taken either direct to the back of multi-pin plug assemblies, or via an intermediate junction block where this will simplify servicing and circuit testing. The aim is to produce a clean enclosed unit with plug-and-socket connections for easy removal.

(4.4) Release Features

When safety circuits are tripped to shut down a reactor the shut-off elements must be released so that they drop to the shut-down position with the shortest possible delay. An electro-magnet with face-to-face contact is undoubtedly the simplest and most effective quick release. It automatically fails to safety and fits in well with circuit requirements, and its dimensional size is reasonable in relation to its load capacity. It can release its load in a millisecond or less and its power consumption need be only a few watts. Fig. 2 shows a typical example of such a system.

The face magnet is particularly suitable for direct-lift systems, but for shaft-driven systems some form of magnetic clutch is required; in this case the released portions of the rotating system have inertia and will limit the acceleration of the released control element. To minimize the unwanted inertia the clutch should be geared as directly as possible to the final winding shaft. This will

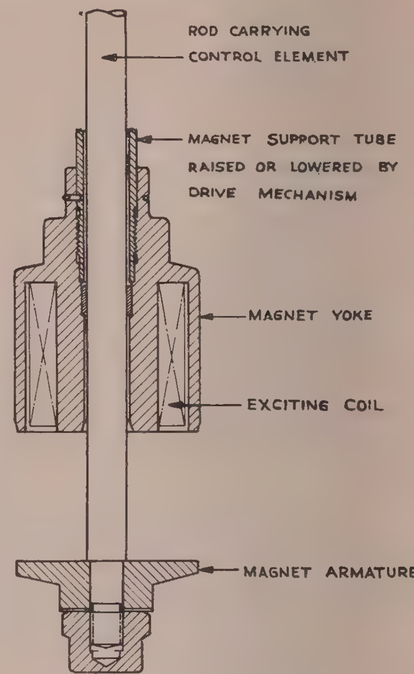


Fig. 2.—Direct-lift magnet for simple release.

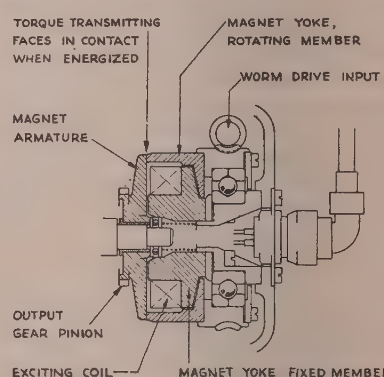


Fig. 3.—Magnetic transmission clutch for torque release.

require a compromise between referred inertia and tolerabl clutch dimensions.

To avoid rotating the magnet excitation coil the method c clutch construction shown in Fig. 3 is used. The magnetic circu is in three parts: a fixed portion of the yoke carries the excitatio coil; an outer portion of the yoke rotates when driven; and a armature plate engages with the driven member when the clutc is excited. The bare metal clutch-faces transmit the load, an wear is no problem, since the clutch is either engaged or fre Any attempt at adding friction faces adds complication an increases the chances of sticking. Release features which involv the use of latches or sears are viewed with some suspicion, fc wear and tear can considerably alter the characteristics of suc devices. No system should be used where a force has to b applied to initiate a release, for the force may not be there when is wanted. The principle should be that a force is applied cor tinuously until such time as a trip is required. The fail-to-safe features must be continually borne in mind at all stages in tl design.

(4.5) Accelerator Systems

Although the initial power drop is rapid when control elements are released, in some systems the elements may be withdrawn well clear of their effective shutting-down position and time will be lost in moving through this distance. To minimize this delay some reactors use an accelerating system to speed up the drop. A typical and well-tried method is shown in Fig. 4. Here the accelerating medium is compressed air, which is always exerting the accelerating force on the shut-off element when it is lifted. It amounts simply to a compressed-air spring which extends immediately the element suspension wire is released.

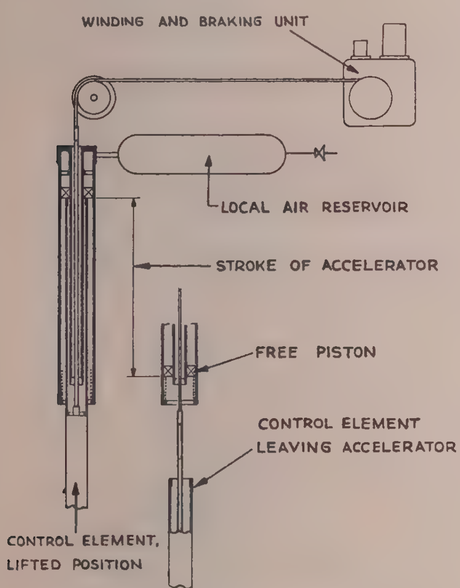


Fig. 4.—Simple compressed-air accelerator.

The mechanism required to lift the elements and bring them to rest is completely separate and can be designed independently. In reactors where fuel elements are moved to reduce reactivity, the effect of movement is apparent immediately and the advantages of added acceleration are less significant. There may, however, be an experimental advantage to be gained by having a rapid and accurately defined shut-down. Such a system has been built into one Harwell reactor and this is described in Section 5.1. Electrical acceleration has been suggested, but the risk of losing the supply renders the idea less attractive.

(4.6) Free Fall Systems

The time taken to fall freely under gravity is usually sufficiently short to satisfy the safety requirements of shut-down. An element falling freely will drop 16 ft in 1 sec, and even if the system has inertia loading which limits the acceleration to $\frac{1}{2}g$, it will fall 8 ft in 1 sec. If the shut-off elements can be dropped just short of bottom position within 1 sec, there will be no appreciable power rise if reactor periods of 10 sec are regarded as minimal for a reactivity trip. The last fraction of travel can be completed relatively slowly, to suit the braking system.

(4.7) Braking and Damping Methods

In order to bring a falling control element smoothly to rest there are a number of possible solutions, but the most desirable methods involve appreciable complication. Some possibilities are electrical or eddy-current braking, pneumatic or hydraulic damping, springs, friction braking or other energy-transfer methods.

If a system is chosen which could fail through, say, loss of current or loss of oil, a further protection stop will be necessary to limit the shock to a value which will not damage the reactor structure. The choice of method is very often settled by the reactor design layouts, but the following comments are worth noting. Electrical braking will give a very smooth deceleration and is worth considering for shaft-driven systems, but it will require a final limit stop which, under fault conditions, must absorb the whole energy. Under normal conditions this emergency stop would act as a relatively solid bottom limit.

An eddy-current brake with separately excited magnets will allow a free fall until a chosen point in travel is reached, when the magnets can be excited and braking can commence. This results in an easily adjustable system, but it has the disadvantage that loss of excitation supply means loss of braking. The system is used, however, on the shut-off system of two Harwell reactors, where the shut-off elements are sufficiently light to permit a reasonable size of shock stop system. The magnet excitation is supplied from batteries, for maximum reliability.

A permanent-magnet d.c. generator will also make a suitable brake if the armature is short-circuited at the required braking point. This scheme would not suffer from loss of supply, but it would impose a rather large inertia load on the system, and has not so far been used.

A permanent-magnet eddy-current brake gives a method of continuous braking which may suit some systems. There is the further possibility of short-circuiting the magnetic flux to avoid braking until required. Damping with pneumatic cylinders has often been considered, but has not so far suited the particular problem to be solved. Oil hydraulic plunger systems offer the best solution for stopping heavy control elements, and this method is invariably used on mechanisms which are housed beneath a reactor. Oil should not be used immediately above a reactor unless very adequate precautions are taken to prevent leakage into the core regions.

An alternative hydraulic brake for use with cable-operated shut-off elements has an oil pump in the winding unit; a braking torque may be obtained by closing the pump outlet so that oil is delivered through a heavily set relief valve.

Springs by themselves are not suitable for checking a falling control element, for they absorb very little energy and the resulting bouncing would be intolerable. Friction spring systems, however, bear examination. One type of friction spring is that formed by a pile of nesting rings with tapered engaging faces; it is known as a 'ring spring' and will carry heavy loads with relatively small compression. To stop a system entirely by this method would involve some bounce and also some doubt about the final rest position. Coil springs can be actuated by cams shaped to supply the necessary friction and to obtain a chosen deceleration. Friction coefficients, however, are uncertain and can alter with use, and therefore the bottom position will vary.

Direct friction braking is quite feasible, but unless it has some control with position it will not suit the requirements. The resulting servo-action complications are likely to be appreciable. Under mechanical energy-transfer methods the flywheel system is probably the most simple. Here the aim is to drive a flywheel with the falling load and to allow the flywheel to free-wheel at the end of the run. To improve on this, if the flywheel is driven by a cable running over a spiral pulley, the effective flywheel inertia becomes steadily greater as the load falls. This gives a relatively easy run to start with and a greater braking force as the spiral radius decreases. From the practical aspect the limitation

is set by the smallest radius through which the wire cable will bend. A Harwell alternative to this form of drive is described in Section 5.3.

(4.8) Enclosure

Improved reliability and protection will result if the control mechanisms are designed into enclosed unit assembles. This principle permits better lubrication, better protection to adjustable features and easy removal or replacement of units. The specially designed enclosed construction is a deterrent to ill-advised alteration to a gear ratio or other basic feature.

The running accuracy of rotating parts will be greatly improved by the rigidity of box enclosures. This form of construction lends itself to spigoted faces for mounting and for motor drives, with consequent true alignment. A design which can be badly aligned or can lose alignment with temperature change may well cause a shut-off element to stick when it is needed.

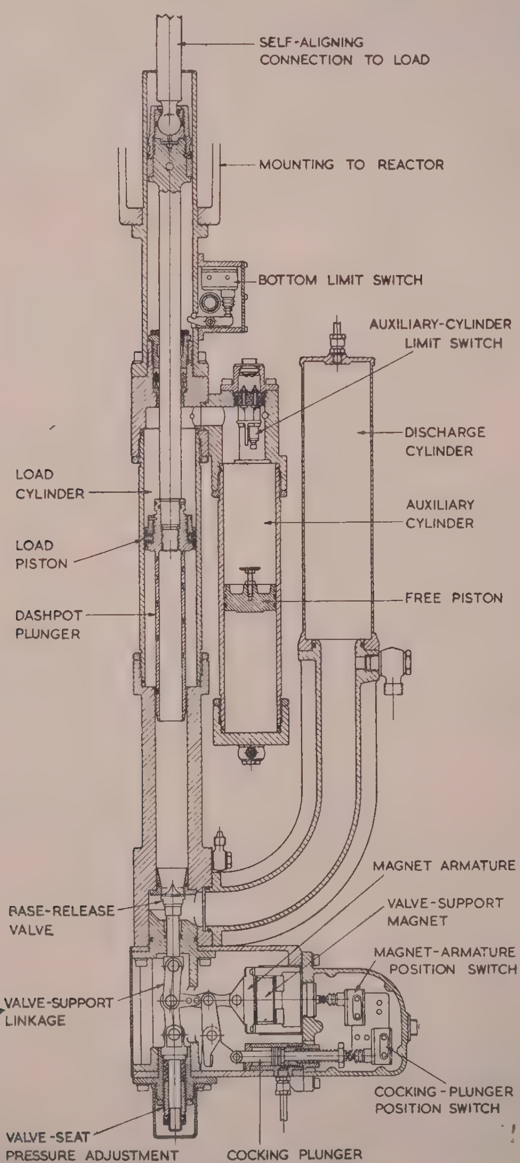


Fig. 5.—Arrangement of hydraulic shut-off mechanism.

(5) SOME HARWELL CONTROL MECHANISMS

(5.1) Hydraulic Accelerated Shut-Off Mechanism

A hydraulic system was developed to accelerate a shut-off element weighing about 360 lb at 10*g* in anticipation of a fast reactor application, so that adequate testing and experience could be obtained. Finally a unit using this system was used as a primary shut-down element on Zephyr, the first Harwell fast reactor, in addition to six smaller gravity-drop control elements.

The operating stroke in this mechanism is between 12 and 13 in, depending on the top limit position, this being a preset stop within the reactor. The mechanism, when lifted, is arranged to apply a continuous load against this stop, so that dimensional changes in the mechanism or its mountings with temperature will not cause any reactivity changes during operation. The actual control element is mounted at the upper end of a vertical shaft assembly fitted with rollers which run in a fixed guide-tube. This forms a carriage which is driven by the mechanism mounted beneath the reactor.

An arrangement of the operating mechanism is shown in Fig. 5, and a diagram of the hydraulic circuit is shown in Fig. 6. From

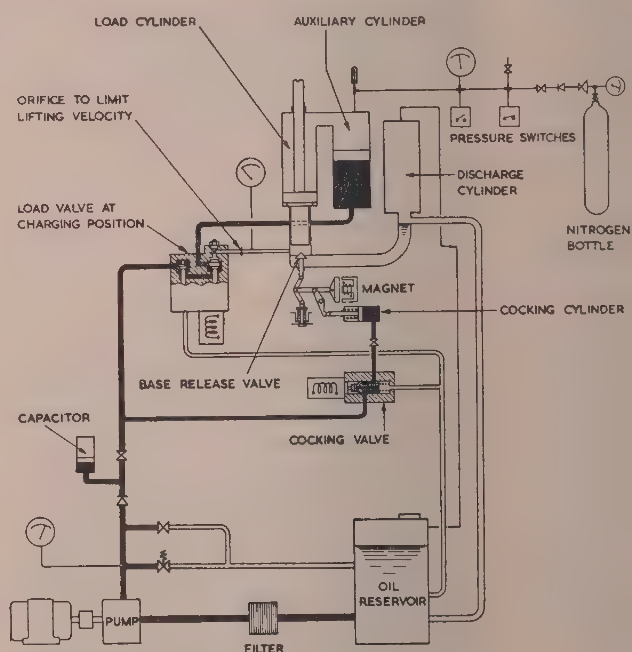


Fig. 6.—Diagram of hydraulic shut-off system.

these diagrams it will be seen that the unit consists of three cylinders, namely the load cylinder, the auxiliary cylinder and the discharge cylinder. The load cylinder is closed at its base by a magnetically-held valve, and a piston in this cylinder carries the load, i.e. the shut-off element. The auxiliary cylinder, which contains a free piston, lies alongside the load cylinder, and both cylinders are connected at the upper end, the common space containing nitrogen at pressure. When it is desired to raise the load an automatic sequence of operations is initiated which proceeds as follows. Oil is pumped to fill both the cocking and the auxiliary cylinders, the load cylinder base-release valve closes, to be held magnetically, and the gas contained in the upper cylinder spaces is further compressed, as shown in Fig. 7 between points A and B, as the free piston rises. The cocking plunger now retracts and permits the load valve to change over and oil pumping to cease. This corresponds to point C in Fig. 7.

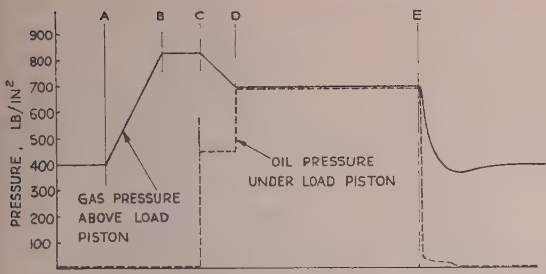


Fig. 7.—Pressure diagram of hydraulic cycle.

The new valve position permits oil from the auxiliary cylinder to flow into the bottom of the load cylinder under pressure, owing to the compressed gas above the free piston. Although the compressed gas is at the same pressure above the load piston, the effective area on the underside of the piston is greater and a differential force, acting upwards, raises the load piston.

As already emphasized, the rate of reactivity addition must be limited to an agreed safe value. A small orifice is therefore built into the oil inlet at the bottom of the load cylinder, and this restriction limits the rate of lift to about $\frac{1}{2}$ in/min. When the load reaches its top limit, i.e. point D in Fig. 7, the auxiliary cylinder still contains a quantity of oil, which remains available to follow up any movement or valve leak, thus maintaining a steady upwards force on the top stop. This action is reversible, and any tendency for the piston to lengthen will result in oil being forced back into the auxiliary cylinder.

The base-release valve is held by its magnet, which is energized by the reactor safety line, so that a trip will allow the valve linkage to collapse and open the valve. When this occurs, the pressure on the underside of the load piston drops to a negligible value and the compressed gas in upper cylinder spaces exerts a resultant downward accelerating force on the load piston. This corresponds to point E in Fig. 7. The ejected oil enters the discharge cylinder with little resistance and drains back to the reservoir.

For the first portion of the downward travel the load acceleration averages about $10g$. During the final 8 in of stroke a decelerating force is applied by a dashpot plunger attached to the load piston and finally brings the load to rest.

The closing force on the release valve is applied by a spring system at the base of the assembly, which is set a little in excess of the possible peak oil load during a cycle. The spring action is trapped, so that extension on release is very limited.

The valve support linkage uses needle roller bearings to minimize friction, and to assist the collapsing action a spring pressure is applied by a switch-operating plunger through the centre of the magnet. In this linkage the advantage ratio rapidly decreases when motion commences, thus diminishing the armature inertia referred to the valve stem as the valve opens. In addition, lightweight construction has been used to shorten further the valve opening time as much as possible.

A series of performance tests were carried out on this unit, and some of the times recorded with the aid of a high-speed ciné camera may be of interest. After release, about 2 millisec are lost during recovery of the valve seating spring, after which valve opening starts. At further 1 millisec intervals the valve openings are 0·005, 0·016, 0·040, 0·080, 0·140, 0·22 and 0·30 in respectively. This latter opening permits almost unrestricted flow, and further movement is controlled by a dashpot under the valve.

An examination of the travel times of the load piston shows that an acceleration of $10g$ is achieved with not more than 5 millisec time lag behind a theoretical $10g$ curve up to the point where deceleration starts, the first 4 in of travel being completed in 0·05 sec after breaking the magnet circuit.

The magnet release-time is small in relation to other time lags, being approximately 3×10^{-4} sec. This is kept short by limiting the excitation of the coil to a value not greatly in excess of that required to hold the load and by suitable choice of a shunt resistance across the coil to increase the current decay rate.

The controlling circuits of the system are arranged to detect any variation from normal, when a trip or a warning will result. The load will also fall readily under gravity if gas pressure is completely lost. The safety of the reactor does not depend on such a rapid-acting shut-off element, since a gravity drop would be adequate. Its particular advantage in this reactor is in connection with the nuclear experiments which involve time measurements after an accurately defined shut-down.

(5.2) Combined-Element Drive Unit

Six examples of a combined unit in which the same mechanical assembly is designed to perform several functions are mounted in a circular group beneath Zeus, the largest Harwell fast reactor. They are used as safety elements, regulation elements and depletion-regulation elements, with two units performing each function. When tripped, the control-element assembly, together with its positioning carriage and connecting members, falls freely under gravity, the total released weight being approximately 125 lb and the distance of travel 19 in from the fully raised position.

The lifting speed is limited by using either an induction motor, for fixed-speed driving, or an a.c. servo-motor for variable-speed driving, as is required for the regulation elements.

Fig. 8 shows the system to consist of a drive unit and an actuator for moving the control element. These main assemblies are fully enclosed, and are lubricated where necessary by oil flow from a small built-in pump. When energized, a magnet at the lower end of a hollow threaded shaft supports the control element via an armature and rod through the centre of the actuator assembly. The threaded shaft with attached magnet, restrained from rotation, is raised or lowered by an output from the drive unit.

The maximum control-element lift can be restricted to any chosen value by stopping the rotation of a splined shaft in the drive output, a friction clutch in the drive train giving protection to the motor. A lead-screw driven by the splined shaft rotates and rises to carry a striker which meets a set stop when the required top limit is reached; this position is adjusted by moving the stop with respect to the striker, the stop being mounted on a barrel which screws on to a fixed mounting, the thread pitch being the same as that of the lead-screw. After adjustment, the stop is restrained from rotation in the required direction by an anchoring pawl which engages into teeth cut on the surface of the stop barrel. The pawl is attached to a tilt lever which releases two top-limit switches before anchoring the assembly.

The control element is stopped accurately at the chosen limit point by this method, and any motor overrun will result in clutch slip. The stop setting is indicated by a micrometer-type scale on the barrel, and for adjustment the pawl is released by a self-resetting push-rod. Since adjustment to this stop alters the potential reactivity of the reactor, it must not be altered without authority. To cover this point, the access door in the drive unit can be opened only when a switched interlock key in the control desk is released by a further key under authoritative control.

For position indication a pair of magslip transmitters are mounted at the top of the drive unit. When extra fine indication is required, a replacement assembly containing three magslips can be mounted in the same position.

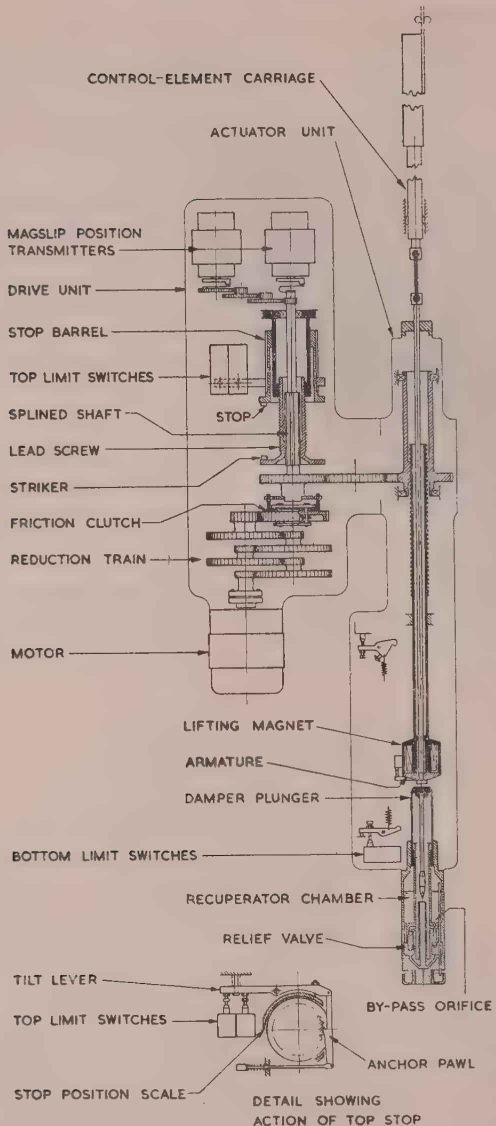


Fig. 8.—Diagram of combined-element drive unit.

Limit switches for the 'down' position are grouped at the lower end of the actuator. Two are operated when the control element is at the bottom position and a third when the magnet is driven down to this same point. A further switch gives warning of approach to bottom, to avoid an undesired trip, and another indicates that the magnet has engaged before permitting the drive to lift. An additional top-limit switch is also fitted in the actuator for protection against overlifting. In this unit a hydraulic damper has been used to bring the falling control element to rest after release. It is basically an oil-displacing plunger with a stroke of 6 in, during which three stages of action are involved: the first provides a smooth pressure build-up until the second stage is reached, when a substantially constant decelerating force occurs, owing to a preset pressure-relief valve; the system is brought almost to rest near the bottom, and the final stage permits a slow creep to the fully-down position.

To cover the possibility of the damper being inoperative, owing to the plunger failing to reset or to possible loss of oil, the complete damper assembly is held in a rubber mounting pre-loaded to a point slightly in excess of the normal decelerating force. Should a control element be dropped with the damper plunger already down, the resilience of the rubber mounting will protect the structure from damaging forces. Fig. 9 gives an overall picture of the complete assembly and indicates the general engineering features.

(5.3) Shut-Off-Element Operating Head

The shut-off-element operating head is a mechanism which contains all the features for operating a shut-off element in a single unit assembly, and six such units are used on Zeus, in addition to those described in the previous Section. They are mounted above the reactor with the shut-off elements suspended by wire cable from a winding pulley within the unit. The load is about 120 lb and the travel 19 in.

The interesting feature in this unit is the method used for bringing the system to rest after release, energy being transferred to a flywheel in a manner which does not appreciably slow the falling element until a large part of the drop has been completed. This is achieved by increasing the gear ratio between the load and the flywheel as the motion proceeds, the flywheel being allowed to free-wheel at the end of the travel.

Fig. 10 shows how the winding pulley will rotate and lift the load when the clutch is engaged and the motor is driving. At the limit of lift the winding pulley is solidly restrained in the lifting direction and limit switches de-energize the motor.

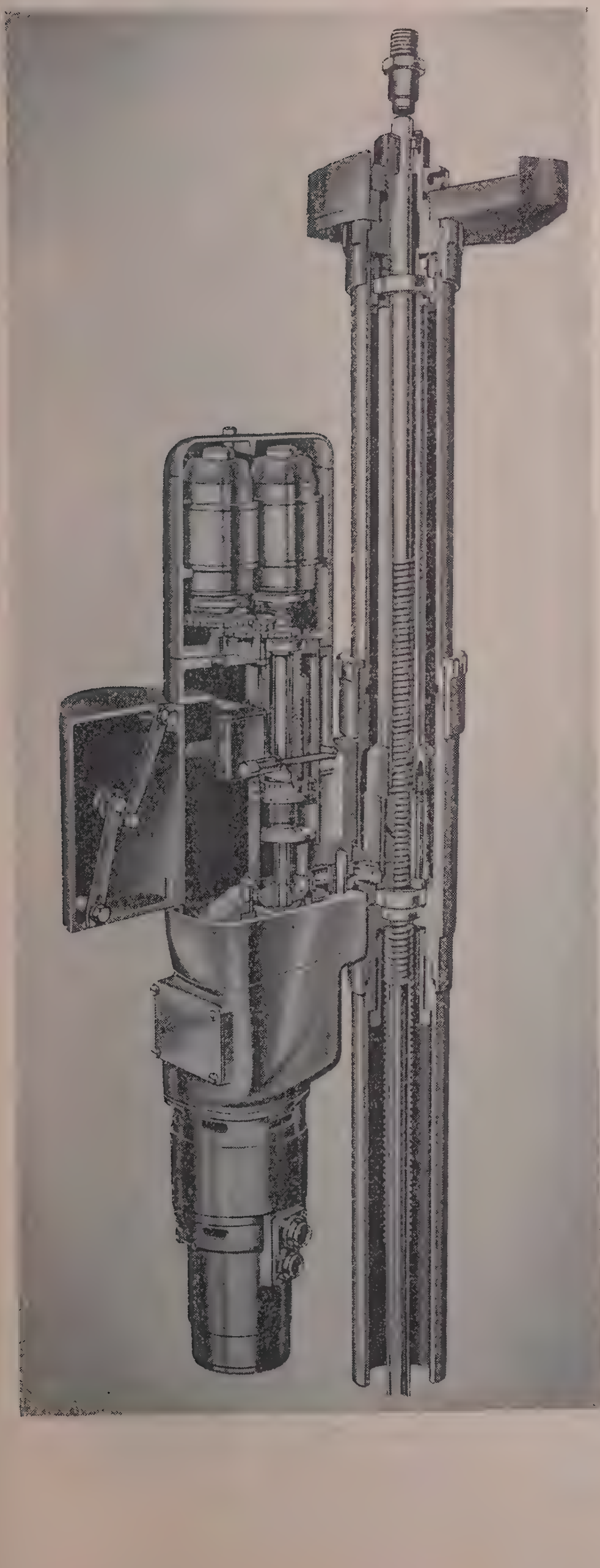
The load is supported by the clutch, which is in turn held by an irreversible worm reduction gear between the clutch input and the motor. When the clutch is released by interrupting the reactor safety-line, the load falls at a rate controlled by the varying gear driving the flywheel.

Fig. 11 shows the action of the varying-gear feature. Two wheels, termed 'driver' and 'follower' respectively, are connected by a link which is arranged to sweep through a range of travel corresponding to the fall of the load. The driver is geared to the winding pulley to suit the required angle of sweep, and the follower is geared to the flywheel with a step-up ratio to suit a flywheel of convenient dimensions. A ratchet in this gear train allows the flywheel to run on when its drive ceases.

When the load is at its top position the connecting link is at a dead-centre position, so that starting movement of the driver does not appreciably move the follower. As the driver continues turning, the follower/driver ratio increases, and Fig. 11 shows how this changes throughout the travel, from zero at start to 3 : 1 at the bottom limit.

As the load falls away from the top position the flywheel drive ratio increases, but its effect is small for the first few inches of travel. This enables the system to move well away from the top position, almost as quickly as in the case of a free fall, before the flywheel begins to reduce the acceleration. In this unit its initial acceleration is $10/11g$, neglecting friction. After a drop of 7–8 in a peak velocity is reached and further travel results in a velocity reduction, energy now being transferred to the flywheel at a greater rate than is gained by the load in falling. When the load has fallen $18\frac{1}{2}$ in below the top position the total energy is 185 ft-lb, of which 175 ft-lb have been put into the flywheel train. At this point the dogs on the winding pulley engage with those on the adjacent torque ring. This is forced to rotate slightly against the restraint of spring plungers which receive the remaining energy to bring the system to rest. The spring plungers have a high friction factor, which ensures a damped check.

After the torque ring has been engaged the flywheel experiences no further energy input, but since it has received almost the whole of the energy released by dropping the shut-off element, it will



(a)

(b)

Fig. 9.—The combined-element drive unit.
(*a*) Drive unit (attached to upper end of actuator).
(*b*) Lower end of actuator.

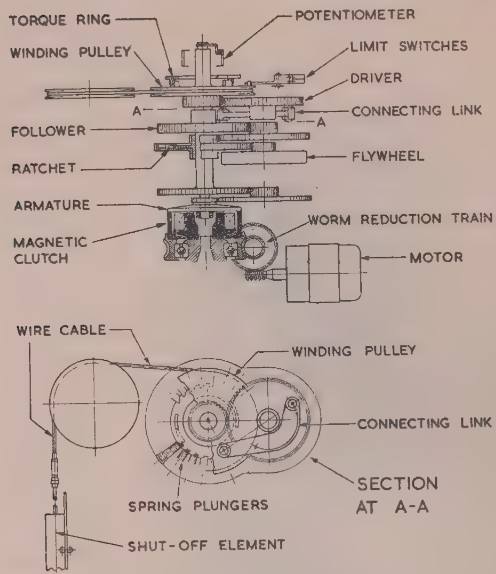


Fig. 10.—Diagram of shut-off element operating head.

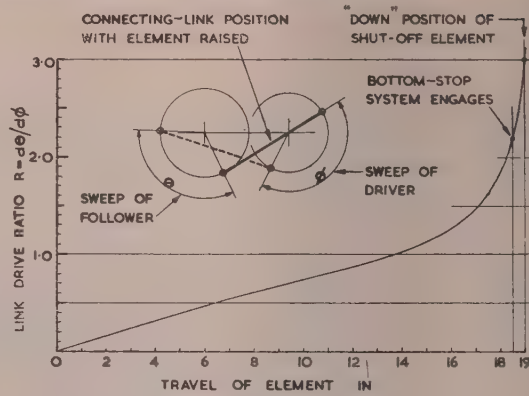


Fig. 11.—Variable-gear-ratio diagram for operating head.

run on freely, owing to the ratchet in the drive train, until friction gradually brings it to rest.

In this mechanism the travel is sufficiently short to permit using a winding pulley which rotates less than one revolution; this enables strikers to be mounted on the pulley for travel stops and for limit-switch operation. It also enables a direct-driven potentiometer to be used for transmitting position indication, this being adequate for a shut-off element which will be used only at a fully-lifted position. As shown in Fig. 12, the complete assembly forms a compact unit which does not require any additional safety-stop system, since it does not depend on any supplies or added fluids to operate the braking system.

Tests on these units show that the performance closely follows that predicted, and operation is agreeably smooth and consistent.

The mechanisms which have been described in the previous three Sections are used on reactors of low power output which have no cooling problems, and therefore a simplified installation results. They are also short-stroke systems, but as mechanism examples they are typical, and it is hoped that they serve to show, in general, the type of mechanism design which control-system drives involve.

(6) SPECIAL PROBLEMS

In a power-producing reactor the primary coolant will be contained in a closed heat-exchanging circuit of which the reactor-

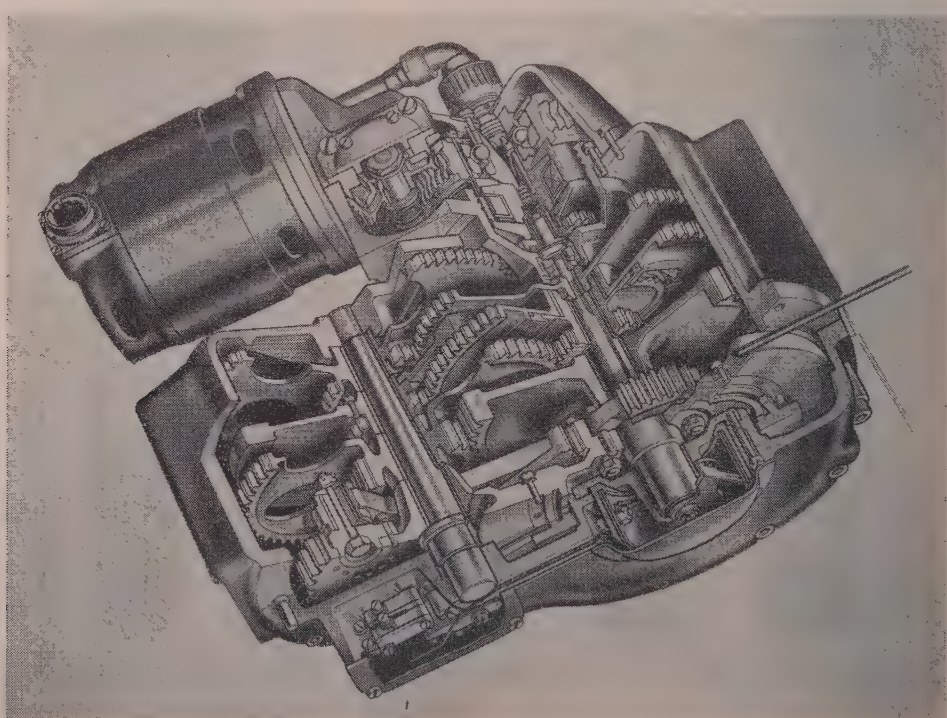


Fig. 12.—The shut-off element operating head.

core vessel forms the central member. The coolant may be a gas, liquid metal or other fluid, and it will be running at an elevated temperature; it may also be under a high pressure.

In gas-cooled thermal reactors the pressure will not be too high to permit the use of re-entrant tubes which reach into the core regions. Control elements can be housed in such tubes and can be operated by mechanisms mounted above each system.

This method will not be suitable for high-pressure vessels or for reactors which require fuel movement for control. Here the control elements will have to operate inside the core vessel, but the control will have to be exercised from outside. This means either driving through the core shell by a direct but sealed penetration, or some induced form of drive which does not penetrate the shell. There is the further possibility of putting all motor drives within the shell, but this solution may bring more problems than it solves.

A high-pressure system using a coolant such as water will no doubt be best controlled by a direct drive using a multiple sliding-collar type of seal which will provide a multi-stage pressure drop and permit very easy sliding of the drive rod. It will leak slightly, but any number of backing-off stages may be used to ensure that the final leak is harmless and that the leakage is controlled at intermediate stages. Reactors using liquid metals under low pressure can be driven by induction motors with sealing shells between the stators and the rotors. They can be released magnetically, and position indication can be made in the same way through thin sealing shells.

Induced driving through thin shells is feasible in a higher-pressure system if the outer drive is enclosed in a pressurized cover held at a pressure similar to that in the core vessel, i.e. to ensure a negligible pressure difference across the thin sealing shells. Although these statements indicate only the general lines on which some future control systems may be driven, the detail engineering of mechanisms which function inside enclosed vessels will require a considerable amount of thought. In addition, testing and operating of such systems will be necessary to prove reliability before installation in a reactor can be contemplated. All this assumes that the many metallurgical problems will have been satisfactorily solved.

Removal for servicing and replacement is also a feature which the design must satisfy, and in view of the high radioactivity of an assembly which has been in use, and the need to continue reactor cooling while removal is being carried out, complicated blanketing seals and shielded flasks will be needed in the same manner as for fuel changing.

It can be seen from these brief remarks that, to solve these problems effectively, control elements and control mechanisms must be designed mutually with the fuel loading and unloading equipment, in addition to the related reactor parts such as core, cooling and shielding.

(7) CONCLUSIONS

While the foregoing remarks do not mention many possible types of control drive, and little has been said of other types which are in existence, an attempt has been made to state the general requirements of any system, to indicate safety aims and to give examples of the type of engineering which has been established at Harwell for control-drive applications in a limited field.

Much interesting design work requiring many exacting compromises lies ahead, and although mechanical movement of solid control elements is usually visualized, the introduction of fluids or gases for control may be desirable alternatives in certain types of reactor.

Both new techniques and extensions to conventional ideas will no doubt play their part, but whatever methods are involved, the development of nuclear power will require reliable design solutions to control-engineering problems.

(8) ACKNOWLEDGMENTS

The author is indebted to colleagues at the A.E.R.E. for contributions which have been made toward the preparation of the paper. Acknowledgments are also due to Mr. A. Frazer Nash for the hydraulic accelerator design and to Mr. A. Payne for the high-speed photography used in obtaining the performance data.

DISCUSSION ON THE ABOVE FOUR PAPERS BEFORE A MEETING OF THE INSTITUTION HELD IN CONJUNCTION WITH THE BRITISH NUCLEAR ENERGY CONFERENCE, 5TH APRIL, 1956

Dr. Denis Taylor: Although the papers deal with experimental reactors, much of what has been said applies also to power-producing reactors, which, however, present new problems and changes of emphasis.

Will the authors justify their method of siting ionization chambers in or near the reflector as a means of indicating the power level? At first sight it might be thought that the chamber should be sited in the centre of the core. This is probably impossible because of life considerations, but more comment is needed to justify the authors' method.

Messrs. Abson and Wade discuss the question of reducing neutron-induced activity and the use of very pure materials of construction. Can they say more about the different materials they have considered? Many materials which appear to have attractive properties from the nuclear aspect, e.g. titanium, might be undesirable from other points of view.

The authors consider producing a chamber which will operate at higher temperatures; this is of considerable importance in power-producing reactors; have they now produced a satisfactory lead-through terminal, and, if so, will they give details?

Should alternative methods of determining the power level be considered? For example, in the swimming-pool type of reactor the γ-ray energies extend over a considerable range (up to about 8 MeV) and it should be possible, using either a scintillation counter or Cherenkov-type detector, to assess the reactor power by recording the fluxes of prompt-fission and neutron-capture γ-rays. In the Cherenkov type this can be done in the detector, but in the scintillation counter it will be necessary to have suitable discriminators in the electronic circuits.

I am disappointed that Messrs. Cox and Walker could not include very much about the analysis of reactivity control rates. This is important, and if all the material were available it would be worth a paper in its own right. Originally, of course, so far as the United Kingdom was concerned, Moore had proposed in connection with temperature-stabilized starting-up that the maximum rate of reactivity addition should be such that it can be absorbed by temperature rise. This very safe procedure has been adopted to some extent, but it involves a very long starting time. In the United States the criteria for the maximum rate of reactivity addition are considered in relation to the speed at which the protection system will operate to ensure a safe shut-down in the event of an accident, and American opinion is that there is everything to be gained by starting up the reactor as quickly as possible consistent with that philosophy. The intermediate procedure, which has tended to become common practice at Harwell and in various Continental countries, involves

starting up the reactor rather faster than the Moore method, but slower than the common practice in the United States. It would be useful to know more about what the various reactivity addition rates really mean from a safety aspect. This can be done only by considering different types of reactor and it involves laborious calculations using analogue computers, but it would be worth while.

Both Mr. Gillespie and Mr. Lockett discuss the method of paralleling shut-down amplifiers to avoid accidental failure due to equipment fault, and both mention the system having three shut-down amplifiers, two of which fail and result in a shut-down. It ought to be possible to analyse this problem properly. I wonder whether the stage has been reached of knowing that the system discussed is the best compromise between cost and safety.

There are other problems, e.g. the paralleling of period meters. Some designers parallel period meters and use the trip circuits to shut down the reactor on the two-in-three principle, but others suggest that its use with trip circuits on the period meters was necessary only during starting-up. Will the authors comment on this? In some cases it is perhaps desirable or necessary to parallel industrial instruments for the measurement of temperature, flow, etc., but this has not been mentioned in the papers. It would be useful to be told either that industrial instruments are so safe that it is necessary to have only one of them, or that the same principles hold good.

Mr. Lockett's two examples are both what might be called 'short-stroke' systems. Can they be adopted for the longer-stroke systems necessary for higher-power reactors? After all, both Zeus and Zephyr are zero-energy assemblies.

Mr. Lockett suggests that enclosing the drive mechanism in the shell itself might make more problems than it solved. Does he really mean this, because many design engineers are tending to use that procedure in high-power reactors?

Mr. Lockett also mentions movement of the fuel itself as a means of effecting control, but at first sight such a method seems to complicate fuel loading. Will he comment on this and state how he overcomes the obvious problems which arise with the method?

Mr. R. V. Moore: Messrs. Cox and Walker summarize very clearly the nuclear characteristics of a reactor and some of the basic measurements needed for its control. For experimental reactors designed to establish the nuclear properties of a new system or to produce a high neutron flux for irradiation, this theory is almost completely adequate, but the development of reactors for power production raises a fresh set of problems.

In general, the thermal characteristics of power reactors attain a much higher degree of significance than in experimental reactors, which are nearly always operating at low or moderate temperatures. Dr. Taylor mentions the importance of the temperature-coefficient effect and its exploitation in the design to increase the safety of those plants.

As pointed out in the paper, two coefficients are identified, one associated with the fuel and the other with the moderator, those quoted being associated with the reactor with a new fuel charge. To be economical, power reactors require long irradiation of the fuel, during which the composition of the fuel changes. A fundamental investigation to ascertain whether these changes have any effect on temperature coefficients is an important item of research.

In power reactors the heat energy has to be converted into useful power. With the heterogeneous type of reactor, the boiling-water cycle excepted, the basic system is to transport the heat from the reactor to a steam-raising unit which supplies the turbine cycle. So far the system of control has been based on maintaining constant-temperature conditions of the coolant transporting the heat between the reactor and the heat exchangers. This has been done mainly to minimize the thermal cycling effec on the plant. The criterion implies an ability to vary the coola mass flow for a variation of power output.

Owing to the non-linear characteristics of heat exchangers, order to keep the return temperature of the coolant from th boiler to the reactor constant, some variation of boiler pressu with the load is involved. From this system a number of contr loops can be distinguished: first, there is that associated with th control of the heat output of the reactor, involving control-ro manipulation and ionization-chamber measurement; secondl there is that associated with the control of the coolant mass flo to keep the rise in temperature through the reactor constant fo varying power; thirdly, there is that relating boiler pressure t temperature of the return coolant to the reactor; and lastly, ther is the control loop of the turbine itself. These fundament control loops can be interconnected in a number of ways. Tw basic systems of control can be distinguished in which the pow change is initiated respectively from the reactor and from th turbine. A thorough investigation into this field of control theor is important, in order that an economic and stable system c control for nuclear power plants can be evolved which full exploits the characteristics of the plant.

Monsieur J. S. Weill (*France*): I should like to ask Mr. Gillespi whether the amplifier is exactly behind the fission chamber.

Why are boron-coated thermo-piles not used to measure th flux in reactors?

How is the mean life of neutrons measured?

Mr. K. Sandiford: I wish to consider the papers from th standpoint of the U.K.A.E.A. Industrial Group Headquarters a Risley, where the basis of reactor operation is rather differen from that at Harwell.

The Industrial Group's reactors are large production reactors as opposed to the smaller experimental reactors at Harwell, an the Group's primary consideration is to keep them operatin safely for long periods at the maximum practicable power. Th difference in operating requirements leads me to suggest a rathe different relative emphasis between nuclear instrumentation an what, for want of a better term, is called physical instrumentatior from that given by Mr. Gillespie.

Mr. Gillespie states that in a small experimental reactor th physical instrumentation is usually very small compared wit the nuclear instrumentation, whilst in a large power-producin reactor the reverse is the case. He has gone on to dismiss th physical instrumentation as being well known and as conformin to standard industrial practice. The physical instrumentation i certainly well known in the sense that it consists in the measure ment of quantities such as rate of flow, temperature, pressure an other commonly occurring variables which have undoubtedl been measured for many years. However, any group responsibl for the design of a power-producing reactor which because of thi fact dismissed the physical instrumentation lightly would b making quite the wrong approach to the general problem o reactor instrumentation. We find that the selection or design o physical instruments and the method of installation requires ver close attention. The following few items of physical instrumenta tion illustrate the point.

First, the measurement of fuel-element temperature is critical and in many cases the maximum power at which a reactor can b operated is determined by the accuracy with which this measure ment can be made. Even in a thermal reactor, such as those a Calder Hall, considerable ingenuity in mechanical design i required to allow connection of a means of temperature measure ment to a fuel element after its loading into a reactor; the same i true of loading fuel elements already fitted with means of tem perature measurement.

A far more difficult problem arises in a fast reactor having

very high rate of heat production from a very small core. Here, temperature gradients of several hundreds of degrees centigrade occur within a fuel element. The problem of temperature measurement is increased because the temperature distribution is not constant but varies with power output and coolant flow, and because the introduction of a means of temperature measurement into a fuel element disturbs the temperature gradient.

Secondly, a relative problem arising particularly in fast reactors for power production is the measurement of the temperature of coolant from any one fuel-element channel through the reactor core before the coolant has mixed with coolant from adjacent channels.

Thirdly, a problem which has already required considerable attention is the measurement of the rate of flow of liquid-metal coolants. It has been made industrially for many years, but it calls for great care in its application to power-producing reactors.

Other problems include the transmission of control-rod position, the computation of thermal power from flow and temperature difference in a multi-circuit coolant system, the transmission of readings through the walls of a pressure vessel or a reactor enclosure, and the accessibility of primary elements for maintenance.

Dr. J. H. Mitchell: I should like more comparison between British and American techniques.

Mr. Gillespie's paper is based on the withdrawal of absorbers to control reactors, although Mr. Lockett suggests alternative methods. Why does Mr. Gillespie limit himself in this way?

I am appalled by the number of d.c. amplifiers with choppers in the system. Much work has been carried out on the a.c. admittance of gas-discharge devices, and I wonder whether the information becoming available can be applied to converting the d.c. techniques to a.c. ones, with obvious simplification and increased reliability. A new approach can be made which could well affect the whole of Messrs. Abson and Wade's paper.

When dealing with shut-down amplifiers, Messrs. Cox and Walker suggest that more complicated methods are now being studied. I believe that every safety device relies for its safety on its inherent simplicity, and I wonder whether the authors are not going in the wrong direction.

Messrs. Cox and Walker suggest that, if the atmospheric n/γ flux ratio is worse than $4n/cm^2/sec$ per r/h, pulse counting might be used, but they do not make it clear how the pulse counting could fit in with the control system.

Mr. H. H. Heath: Messrs. Cox and Walker state that natural convection is of little avail in removing the fission-product heat from a plant which has been operating in the megawatt region. I doubt this, for in a large power reactor much heat can be lost from coolant ducts and pipework. Should it not be an axiom of design that a reactor can lose its fission-product heat by natural means, so that it is safe from overheating if all forced cooling is lost?

Mr. Lockett mentions that at Harwell they like to have two distinct methods of operating the control rods. Why is this so? Often in a reactor the space is restricted; a mechanism is then evolved which is considered suitable and any alteration is regarded as a retrograde step. Why, then, should a second mechanism be installed which, one must assume, is worse?

Dr. J. J. van Zolingen (*The Netherlands*): In the Netherlands preparations are being made to build a suspension reactor with circulating fuel, and zero-energy experiments are about to start. In a power reactor of this type there are some of the control difficulties mentioned by Messrs. Cox and Walker, but there may also be some outstanding advantages.

First, because the fuel is in the form of enriched uranium-oxide particles of about 10μ diameter, the fission products are shot out in the liquid (H_2O)* moderator and may be removed from the system by a continuous purification process. This almost eliminates the effects of xenon poisoning and, at the same time, eases the problem of starting up after shut-down periods of any length. Moreover, the transient effects after a change of power level are greatly reduced, and the continuous purification appears possible by comparatively simple means.

Secondly, because of the extremely strong thermal coupling between the uranium-oxide grains and the liquid moderator, full advantage can be taken of the very strong negative temperature coefficient. There will be hardly any thermal lag between the fuel and the moderator, which also facilitates control.

A point arising with all types of circulating-fuel reactors is that, by pumping round the suspension, part of the delayed neutrons are emitted outside the reacting vessel. This, of course, will have a bearing on the controllability of the reactor as a whole, but this influence may be rather small when the speed with which they are pumped out is not too large.

Mr. R. J. Smith: It is interesting to note that, although the fundamental functional and operational distinction between experimental and power reactors has been clearly stated, Mr. Gillespie expresses the view that, so far as instrumentation is concerned, differences are mainly in detail. Does he consider this satisfactory? In particular, has the time come when it is possible to reduce the scale of neutron-flux instrumentation in power reactors?

Messrs. Cox and Walker emphasize that the significant application of neutron-flux measurement is in the sub-critical state, whilst the short-term control function is also important. Trips, operating from excess flux and possibly low period, will be required, but a multiplicity of recording and indicating instruments seem unnecessary at power levels.

On the subject of fission-product radioactivity, it has been suggested that an ion chamber could be used to give an indication of that effect by making it function in part as a fission chamber or by using an auxiliary fission chamber. Have the authors any comment on this suggestion?

The value of an analogue computer in solving control problems has been stressed by Messrs. Cox and Walker. In particular, the analogue computer is ideally suited to the determination of transient excursions in temperature and other parameters under various fault conditions.

When analysing reactor starting-up to determine temperature overshoots occurring with rapid rates of reactivity addition, would it not be more accurate—if not quite so simple—to employ integrated power-time as a measure of the rise in temperature of the fuel element, on the assumption that the energy released is not removed by the coolant?

Mr. R. Parr: Temperature coefficients have a profound effect on the dynamic performance of reactors. Of particular significance also are the time relationships between power changes and temperature changes. I am therefore surprised that Messrs. Cox and Walker introduce the concept of an equivalent power coefficient, for, except in very special cases, this method of approach is so approximate as to be of little value. In the particular reference from which the coefficients are derived it is pointed out that appreciable time lags exist between power and the corresponding temperature change; thus there might be considerable power surges before the characteristic illustrated in the paper was achieved.

The authors point out that delayed neutrons are very useful in a reactor, for they exert a potent stabilizing effect; but is a reactor without delayed neutrons in fact uncontrollable? I suspect that it depends on the reactor characteristics and, in particular, on the temperature coefficients and time lags between power and the

* In the final experiments, H_2O will be replaced by D_2O.

appropriate temperatures. In general, however, I do not agree that a reactor without delayed neutrons is uncontrollable, otherwise there will be little hope of success for some of the circulating-fuel reactors proposed by the Americans. Broadly speaking, much of the complexity of reactor instrumentation is introduced because the instruments must derive their signals from a low-power source, i.e. ion or fission chambers. Is there any possibility of a device being produced which is actuated by neutron flux, but which produces a signal at a reasonable power level?

Mr. J. H. Bowen: Mr. Gillespie's statement that large values of negative reactivity are ineffectual in causing a rapid fall in operating level is hardly supported by Fig. 6 in the paper by Messrs. Cox and Walker.

Does Mr. Gillespie see any advantage in making the speed, rather than the position, of the regulating-rod drive proportional to movement of the knob, since it introduces one further integration into the control sequence? It does not follow that the heat output of a power reactor must be kept in step with load demand. The coupling between the two might be very loose, surplus steam merely being condensed and recirculated.

Referring to Fig. 10, is it not preferable to arrange the second set of contacts of the primary measuring elements directly in series as a duplicate trigger circuit? Safety cannot be increased by interposing additional relays.

It is suggested that a combination of three shut-down channels allows each instrument to be tested *in situ*. This is also true of two channels. The argument is surely that two are not safe, since one might fail to danger, when the other would be unable to produce a shut-down.

The shut-down amplifier shown in Fig. 12 still has certain possibilities of failure. In particular, the bad contact at the earth end of the resistor labelled 'set trip level' is a failure to danger. Would Mr. Gillespie agree that most of the residual changes can be overcome by making the amplifier trip if the input signal departs from the reference signal?

Referring to Fig. 2 of the paper by Messrs. Cox and Walker, it is worth noting that certain American data commonly used are derived from calorimetric measurements, which require correcting for the escape of γ-energy.

The curves shown in Fig. 5 would be more useful if the following information were added: the uranium and graphite time-constants; the source power; the starting value of reactivity; and the equilibrium ratio of power to temperature for that reactor.

In the first part of Mr. Lockett's paper there is a general inclination to rely on interlocks to secure foolproof operation, which tends to transfer responsibility for safety from the operator to the maintenance engineer.

It is suggested that individual control elements ought not to be engineered to move in sequence, since it is then always possible for more than one to move, owing to circuit faults; yet banks of elements are allowed to be moved in sequence, which seems to be open to the same objection.

The insistence on gravity shut-off, as opposed to other forms of stored energy, seems reasonable if all the shut-down equipment can be made independent of maintenance. The elaborate shut-down circuits described by Mr. Gillespie shows that this is not so.

Mr. Lockett recommends a sliding-seal arrangement for control rods in a pressurized vessel, but the possibility should be considered of the control rods being blown out of the reactor in the event of mechanical failure.

Dr. J. B. Birks: In most fields of nuclear physics the gas-ionization counter, the Geiger–Müller counter and the proportional counter have been largely superseded during the past decade by the scintillation counter. Scintillation counters have come into general use throughout the whole field of pure and applied nuclear physics because of their simplicity, their higher detection efficiency, their ability to discriminate against other radiations, their faster response time and their higher counting rate.*

It is therefore suprising that the authors have not considered their use in the field of nuclear-power technology.

I have made an approximate calculation of the size of the scintillation-counter element required to replace the gas-ionization chamber RC/1, and to have a similar detection efficiency. The RC/1 is about 9 in long and 3½ in in diameter. The scintillation crystal, i.e. the sensitive element corresponding to the chamber, would be only about 1 mm^3. This tiny solid element, linked by a light guide to a photomultiplier outside the reactor, could be simply and accurately located. Several such elements, placed at various points within the reactor, could be used for control purposes, thus reducing some of the technical difficulties referred to by the authors. Furthermore, scintillation counters give counting rates higher than ionization counters by factors of more than 1 000.

By suitable choice of light guide (e.g. quartz) and crystal materials, they can be less prone to radiation damage than the gas-counter materials. The fluorescent organic crystals, like anthracene, belong to a group of polycyclic hydrocarbons which are much less susceptible to radiation damage than other hydrocarbons or similar low-density materials containing nuclei of low atomic number. Among the inorganic crystals there are phosphors such as calcium tungstate which are virtually immune to radiation damage. I therefore anticipate a much longer operational life for a scintillation crystal than for a gas counter. Moreover, the simplicity of the crystal element means that it can be readily and economically replaced as required.

Dr. Taylor refers to Cherenkov counters; I understand that they are restricted to particles travelling near the velocity of light, and are thus unsuitable for neutron detection.

Mr. B. H. Stonehouse: From Mr. Lockett's paper, the requisite accuracy of control-mechanism position indication appears high. Must the physicist really have an indication of reactivity changes correct to 1 part in 10^5 for a power-producing reactor? Differential expansion between the control mechanism and the reactor-core structure is likely to obscure such small changes in reactivity unless the temperatures throughout the structure are constant.

The servo-controlled induction-motor drive for control mechanisms, mentioned by Mr. Gillespie, suffers from the drawback that the remainder of the mechanism must be designed so that no reverse torque is applied to the induction-motor shaft. How has that difficulty been overcome?

The control-mechanism actuators for pressurized gas-cooled reactors may be mounted outside or inside the pressure vessel. If outside, the design of the shaft seal is the principal problem; it must be gas-tight yet have a low frictional drag on the shaft so that the shut-off duty is not seriously affected. If the control mechanism and acuator are mounted inside the vessel they must work in an ambient temperature of up to 150–200° C and be utterly reliable with very infrequent maintenance. Electrical windings and insulation can meet those conditions, but there is a difficult bearing problem. A lubricant, if used, must not deteriorate appreciably at the high temperature and must not contaminate the circulating gas. Impregnated and self-lubricating bearings should normally be used. The construction of the control mechanism should be made as simple as possible, even if this results in greater complexity in the associated external electrical control-gear, which operates under normal conditions.

[The authors' replies to the above discussion will be found on page 612.]

* BIRKS, J. B.: 'Scintillation Counters' (Pergamon Press, London, 1953).

DISCUSSION ON 'THE CONTROL AND INSTRUMENTATION OF A NUCLEAR REACTOR'* BEFORE THE NORTH WESTERN CENTRE AT MANCHESTER, 1ST MAY, 1956

Mr. J. W. Binns: The author does not mention the measurement of reactor fuel consumption, or burn-up. Such measurements can be made, and the author's views would be of interest.

From the practical and maintenance aspect, what are the author's views on the use of plug-in relays, etc., of the telephone type?

The author places great emphasis on component reliability and the provision of fail-to-safety equipment. What are his views on the provision of suitably reliable or guaranteed power supplies to instruments employed in the trip or safety circuits, etc.?

Mr. H. Morris: In the gas-cooled reactor the following two conditions are important:

(*a*) In any system of control it must be possible to shut down the reactor, notwithstanding any outside circumstances.

(*b*) The control of the reactor should be such that the fuel-element temperature does not exceed the design figure—a circumstance which will increase the risk of failure of the fuel-element cartridge.

The consequences of failure in either of these two cases does not necessarily mean disaster, bearing in mind the negative temperature coefficients of graphite-moderated reactors, which would act to offset the effect of these failures, but there is a quick response of the fuel elements to temperature so far as flux change is concerned. However, failure to control either effect can mean replacing the reactor fuel, since contamination of the cooling system will take place. This could embrace ductwork and heat exchangers, and the cost of a complete change of fuel could well be about £500 000, even allowing for the fact that the fuel can be reprocessed for further use.

Although the author refers to the detection of burst fuel elements, he does not attempt to describe the current thoughts on this for the present, and probable future, types of gas-cooled reactor.

The author's reference to safety rods, shut-off rods and regulating rods suggests that there might be three separate systems of control rod. Although this might be true of the earlier reactors, such as Bepo and at Windscale, there are other considerations when the core is contained within a pressure vessel. Here every ingenuity should be exercised to minimize the number of openings into the pressure vessel. This means performing many functions, such as control, charge and discharge of fuel elements, and measurements of fuel temperatures, through a single hole. The efficiency and safety of a control system under such conditions is not easy to ensure; so much so that, in addition to dual circuits designed on a fail-to-safety basis, gravity fall-in of the control rods under emergency shut-down conditions should be regarded as essential. The ability to withdraw control rods once the reactor has been shut down is also essential, for it is unwise not to have a certain amount of negative reactivity still available for insertion when refuelling a reactor after a long irradiation period.

On the question of fuel-element-temperature measurement, there are many complications besides the somewhat easier task of providing the right type of thermocouple, and compromises have to be made on the actual point at which the temperature is to be measured. Neutron-flux peaking at the limiting effective radius of the control rods can result in temperatures on the cartridges being higher than would normally be the case at the radii at which they are placed within the core.

* GILLESPIE, A. B.: Paper No. 2058 M (see p. 564).

Mr. W. Macrae: The galvanometer should not be forgotten for the measurement of ion-chamber current. Although it is suitable only for measurements at the upper end of the power range, it has the advantage of not requiring external supplies and so continues to indicate under all fault conditions.

In a power reactor it is essential that at all times the ratio of heat generated to coolant flow must not exceed the design value. The maximum withdrawal speed of the control rods is determined by start-up conditions. A rate judged to be safe at start-up results at full power in an increase in fuel temperature of about 1° C per minute, and thus extremely fast action of the safety circuits is not essential. However, reduction in coolant flow due to pump failure is likely to cause a rise in fuel temperature of about 1° C per second. The inference is that assurance of coolant flow and rapid tripping of the reactor in the event of a fault in the cooling circuit are more important when the reactor is at power than protection against accidental motoring out of the control rods.

Mr. J. H. Bowen: The operation of a reactivity meter depends on the differential of a logarithmic signal thus:

$$\frac{d}{dt}(\log n) = \frac{1}{n}\cdot\frac{dn}{dt}$$

which, from eqn. (7) of the paper, becomes

$$\frac{\Sigma\mu_s A_s \varepsilon^{\mu_s t}}{\Sigma A_s \varepsilon^{\mu_s t}}$$

This is plotted as a function of time in Fig. A, for an abrupt change of reactivity of 0·2%. It will be seen that the instantaneous value of the output signal at 0·1 sec is 20 times its equilibrium value, and at 1 sec is twice its equilibrium value. The actual output of the circuit depends on the circuit's smoothing characteristics, and Fig. A includes a curve showing the maximum output expected from circuits having the indicated time-constants. Thus, a 1 sec time-constant leads to a maximum signal three times the equilibrium value. In order to keep the transient signal to less than 20% above equilibrium, a time-constant of 10 sec is required. Time-constants of this order will prevent the circuit from responding quickly to true danger signals; thus, a reactivity meter of this type is unsuitable for use as a trip device in normal operation.

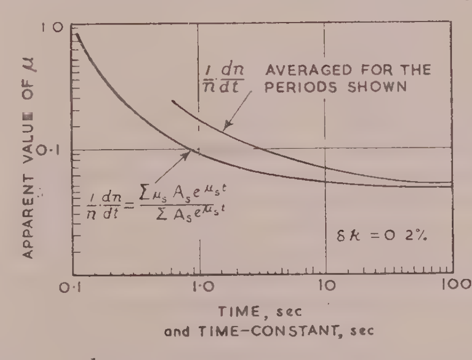


Fig. A.—$\frac{d}{dt}(\log n)$ as a function of time for $\delta K = 0{\cdot}2\%$.

[The authors' replies to the above discussion will be found overleaf.]

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Mr. A. B. Gillespie (*in reply*): Dr. Taylor asks whether the two-out-of-three system of paralleling shut-down amplifiers is the best compromise between cost and safety. This system is the simplest arrangement which permits one instrument either to fail to safety without producing an accidental shut-down or to fail to danger without preventing the satisfactory operation of the safety line on the subsequent occurrence of a genuine reactor fault. In most reactor installations this would be accepted as a reasonable compromise between cost and complexity on the one hand and safety on the other. Other arrangements, however, are possible, and the system adopted will also depend on special conditions appropriate to the particular reactor.

On the question of paralleling trips in period meters, the distinction is not so clear-cut and both systems have advantages. In general it seems that on reactors which run at power for long periods and are shut down and started up only very infrequently, a single period-meter trip with short-circuiting switch will be adequate, but on experimental reactors which are frequently started up, shut down and run at reduced power, a parallel arrangement is preferable.

With industrial instrumentation the same principles hold good. In many cases the switches in the safety line are operated from recorders and there is a greater probability of failure to danger than failure to safety. In such a case a one-out-of-two system might be a reasonable compromise between cost and safety. In a study of this problem in connection with a high-flux research reactor at Harwell it was decided to use a one-out-of-three system on the industrial instruments and a two-out-of-three system on the nucleonic instruments, since this permits grouping of industrial and nucleonic instrument contacts in three sections of the safety line and allows any one section to be bridged for maintenance purposes without preventing operation of the line on the occurrence of a reactor fault.

In reply to Mr. Weill, it is desirable to keep the head amplifier as near to the fission counter as possible, since extra input capacitance cuts down the pulse size and separation allows a greater possibility of spurious pick-up on the connecting lead. Where this is not possible for reasons of maintenance or high-temperature working, it is necessary to secure extremely good earthing between the counter and the head amplifier, and at Harwell a tubular extension of the counter body, clamped solidly to the head amplifier, is preferred to a cable connection.

Mr. Sandiford's contribution on the special problems which arise in connection with the industrial instrumentation is very welcome and shows clearly the need for ingenuity and detailed attention to design. It was considerations of space, which compelled me to treat the matter briefly, but there is sufficient material on this aspect to form a separate paper.

In reply to Dr. Mitchell: I mentioned at the beginning of the paper the alternative methods of controlling a reactor and then subsequently limited myself to absorbers to avoid confusion in the text and because this is the method most frequently used.

Mr. Smith asks whether it should be possible to reduce the scale of neutron-flux instrumentation in power reactors. Whilst nuclear-power instrumentation is necessary during start-up and also at power level for short-term control and for the rapid operation of safety instruments, thermal instrumentation plays a more dominant role, and economies in neutron-flux measuring instruments should be possible. One instance has already been given in the use of a single period-meter with trip on a power reactor, whereas several such instruments would be considered desirable on an experimental reactor.

In regard to Mr. Bowen's query relating to the fall in power after the application of negative reactivity, I was thinking more in terms of small experimental reactors which are frequently starte up and shut down and in which shut-down power is many decade below the running power. The initial drop is, as Mr. Bowe points out, very dependent on the applied reactivity, but ther after the power decay is determined by the delayed neutron and for a fall through several decades the time to reach shu down is much less dependent on the applied reactivity.

In comparing velocity and position servo mechanisms for th regulating-rod drive, both should be assumed to be subject to th same maximum rate of addition of reactivity. The positic servo, while removing an integration from the control loo introduces a time delay proportional to distance moved as we as a transient phase on starting. The effect on closed-loo stability is not easy to visualize, and the problem is at presen undergoing investigation on a simulator designed to stud automatic-control problems, particularly on noisy reactors.

I agree that it is unnecessary for the reactor heat output keep in step with the load demand for short-term variations, b it is uneconomical if the plant has to run for any length of tim on reduced load. Whereas this might not often apply to lan based power reactors, it does apply to propulsion units, whe normal load is only a fraction of the maximum output of th plant.

Mr. Bowen's suggestion to connect the second set of contac of the primary-measuring elements in a duplicate series circu would increase the safety of the shut-down circuits shown Fig. 11. Relays, properly maintained, have proved one of th most reliable elements in reactor-safety circuits.

I agree with Mr. Stonehouse that no appreciable rever torque should be applied to the induction-motor shaft. Th reduction gearing between motor and regulating rod, howeve is so large that the reverse torque is negligible, and it is customa to include a non-reversing gear train somewhere in the drivi mechanism.

In reply to Mr. Binns, the fuel consumption or burn-up in th reactor is usually assessed from a knowledge of the initial char and the total megawatt-days run. Other items of informatic which assist in proportioning the burn-up among the individu fuel elements are a knowledge of the flux distribution througho the reactor and a record of the changing balance positions of th control members. After removal, measurements could be mad on the fuel elements themselves, but would be complicated by th handling difficulty, and might not be possible for some conside able time after removal.

Plug-in relays have not been used to any considerable exter because a sufficiently wide range does not exist. In addition, is customary to put in a particular relay set all those rela associated with one control function, e.g. shut-off rods; th can result in many wires going direct from one relay to anoth within the relay set and not having to be brought out through plug-and-socket joint, which results in improved reliability.

To date, a mains failure results in a reactor shut-down, an it seems rather impractical, particularly on high-power reactor to have a guaranteed supply to keep the reactor running in su an eventuality. A guaranteed supply is necessary to mainta essential cooling in operation during a mains failure, and such reactors it is customary to run the control instrumentatic also from that supply. On zero-energy experimental reactors the is little or no need for a guaranteed supply.

In reply to Mr. Morris, a great deal of work has been do on the wire-machine type of burst-fuel-element detector as fitt to Bepo, Windscale and Calder Hall, and for reactors of th Pippa type it seems the best system to use. On future types reactor this might not necessarily be true and other method

such as delayed-neutron monitoring and bulk γ-monitoring of the coolant, might offer advantages and should be considered.

Mr. Macrae suggests a galvanometer to measure ionization-chamber current. This has already been done to some extent, in that one ionization chamber at least is polarized from batteries and has a sensitive microammeter in the signal lead to the d.c. amplifier. This provides an indication of nuclear power over the top decade in the event of complete mains failure.

Messrs. R. J. Cox and **J. Walker** (*in reply*): We agree with Dr. Taylor that the criteria for deciding in a particular reactor the maximum rate at which reactivity should be added are a problem that is becoming increasingly important. The criteria used in the past have been rather arbitrary, but completely satisfactory for reactors with a low available excess reactivity. However, now that reactors with much higher power ratings and higher excess reactivities are being built, it is an appropriate time to reassess the criteria. With the analogue computers now available, the problem can be studied easily for a wide range of reactor types and parameters. A certain amount of work along these lines has been done at Harwell with quite interesting results, but it is apparent that for a given reactor type such parameters as temperature coefficient of reactivity and thermal time-constant are of paramount importance, and therefore the results are dependent upon the detailed design of the reactor. That work is, however, of sufficient interest for consideration by a university laboratory.

Mr. Weill raises the question of the measurement of the mean lifetime of neutrons. This is not an easy measurement. Equipment has been built at Harwell to obtain values by measuring the transfer function of the reactor. A rotating-shutter arrangement would produce a sinusoidal variation in reactivity of the reactor and consequently a sinusoidal modulation of reactor power. By relating the amplitude of the power variation with the frequency, the mean neutron lifetime could be obtained, and by using the same equipment at lower frequencies (below 10 c/s) the delayed-neutron abundances could be obtained.

Mr. Moore illustrates some of the problems involved, and we believe that much work is required on the characteristics of steam plant as part of a control loop. In particular, studies should include variable-temperature systems as well as variable-coolant flow, and a correlation of information on heat-exchanger transfer functions and coolant mixing would be valuable.

In reply to Dr. Mitchell, we do not believe that we complicated the design of shut-down amplifiers unnecessarily. It is usually very simple to arrange for a reactor to shut down quite infallibly. Any complication arises from the need to keep the reactor running and not prone to unnecessary trips due to component failure. By using more instruments in coincidence systems it is possible to have the same degree of safety but considerable reduction in spurious trips. Since this requires more components, it is obvious that a compromise has to be made, based on the probabilities of such failure, the costs of refinements and the cost of reactor outage time.

Dealing with Dr. Mitchell's remark on integrating pulse-counting systems with control, we would point out that the pulse-counting equipment is usually involved only at start-up, where its function is confined to safety rather than control. Neutron-flux monitor design and siting should be such that more than this is not required from pulse counting.

As Mr. Heath suggests, a reactor design should make as much use as possible of natural cooling for the removal of fission-product heat. It was our intention merely to point out the magnitude of the heat quantities involved, and we would be very interested to see a reactor design in which Mr. Heath had achieved his ideal.

We note with great interest the pioneering work being carried out in Holland on suspension-type circulating fuel systems, as reported by Dr. van Zolingen. Removing xenon poison has immense value in high-flux systems, but it would be interesting to know the cost and complexity of chemical plant involved in fission-product removal and the maintenance difficulties which would be encountered. Remarks on the small significance of reduction of delayed-neutron abundance would carry more weight if the times for fuel inside and outside the reactor could be quoted, as these must be fixed by heat-transfer rather than control considerations. Inevitably a loss of delayed neutrons must seriously alter the transfer function of the reactor, both in gain and phase lag, at the frequencies of interest for the control system.

All the experience of running reactors has been, of necessity, with experimental reactors. Now that the U.K.A.E.A. is building power reactors, we agree with Mr. Smith that the time has come to consider how much neutron-flux instrumentation is necessary for power reactors.

When using an analogue computer to predict temperature overshoots occurring with rapid rates of reactivity addition, we used the technique of integrated power-time as a measure of the rise in temperature of the fuel element. However, the transient must occupy a comparatively short time. It could not be used for the type of case illustrated in Fig. 5. Incidentally, this Figure was intended merely as a pictorial presentation of the effectiveness of the temperature-stabilized start-up system. Mr. Parr and Mr. Bowen would apparently have preferred us to present data for a practical system such as a graphite-moderated system, where uranium temperature effect is quite quick-acting, but some moderator temperature effects have a time-constant of some hours. Allowing for the time-constants would have caused the power in the region of 800 sec to be rather higher but would not make a great change in the time to reach 200 MW.

In answering Mr. Parr we would point out that a reactor with no delayed neutrons and running at low power would have a transfer function with a 90° phase lag at all frequencies with a gain that fell from infinity at zero frequency by 6 dB per octave. This would be very difficult to control. The delayed neutrons provide a phase advance in the right frequency range to simplify the control system. At high powers, where the temperature coefficient of reactivity is effective, the gain has a finite value and zero phase shift at zero frequency. With circulating-fuel reactors the loss of delayed neutrons is not quite so serious as Mr. Parr tends to suggest. Also, as pointed out by Dr. van Zolingen, the heat transfer from the fuel to the coolant is so good that the temperature effect is quite quick-acting. This extends the range of frequencies over which the phase shift is less than 90° lag up to the region of a few tens of cycles per second. This provides the necessary phase advance for the control system. A heterogeneous reactor without delayed neutrons would be much more difficult to control.

We agree with Mr. Bowen that the failure in the a.c. shut-down amplifier he postulated, although quite improbable, does constitute a failure to danger. We have already redesigned the amplifier so that a warning is given when the trip setting is too far removed from the actual power level; in other words, when the reactor is being excessively cooled. This is desirable for the operation of the reactor. Also, if only one of the three amplifiers gives this warning, it is probable that either the particular fault has occurred or that the ion-chamber connection lead has developed a short-circuit.

The curves in Fig. 1 are taken from the paper by Untermeyer and Weill (Reference 1 of the paper) and include the whole of the γ-energy release.

Messrs. W. Abson and **F. Wade** (*in reply*): We agree with Dr. Taylor that there will be increased difficulties in the use of neutron detectors in the main reactor core, owing to radiation-damage

effects. By siting the detectors outside the core it is possible to choose suitable radiation levels to ensure a long life. Apart from these considerations there is another important advantage in choosing a detector position outside the core, since the flux level will generally give a better indication of the total neutron power than at a particular point in the core. This applies particularly to the heterogeneous reactor, where the flux distribution in the core varies with the arrangement of fuel elements. Movement of control rods will also produce local disturbances in neutron flux which might be much greater than the total change in power. These and other local variations are smoothed out if the neutron detector is placed outside the main core.

When low residual activities are required, aluminium is a convenient material to use for ion chambers because of its availability in a pure form. Aluminium itself has a relatively low activation cross-section coupled with a short half-life (sautration activity per gramme in a flux of 10^{12} n/cm^2/sec: A_s, $4\cdot8 \times 10^9$ disintegrations/sec; and half-life, $2\cdot3$ min). Other materials of interest for low residual activity are limited in number. Magnesium has an activation A_s of $1\cdot3 \times 10^8$ and a half-life of $9\cdot3$ min. In pure form it is not an attractive constructional material and magnesium-zirconium alloys are preferable. An ion chamber made from this alloy would have a lower residual current than an aluminium chamber during the first 15 min or so after shutting-down, but the current resulting from longer-lived activities would be a few times higher than that quoted for the RC/1 chamber made from $99\cdot8\%$ aluminium. Titanium has an activation A_s of 9×10^7 and a half-life of $5\cdot8$ min, and it offers the possibility of making brazed connections to other metals. Care will be necessary to avoid undue absorption of neutrons in the titanium, because the total absorption cross-section is considerably greater than the activation cross-section. Pure iron (free from Mn, Co, Cu and Zn in particular) is also of interest: its A_s is 3×10^7 but its half-life is 45 days. It has the disadvantage of poor corrosion resistance and cannot be used, for example, in the water shield of a swimming-pool reactor.

A lead-through seal similar to that used in the RC/1 chamber, but using pure aluminium foil in place of lead foil for the vacuum seal, has been operated satisfactorily at 250° C. An alternative approach to the problem of high-temperature operation is the use of metal-ceramic seals of the type being developed for ceramic-envelope valves.

Dr. Taylor suggests that the measurement of the so-called prompt-fission γ-rays might be used to indicate power level, discrimination against fission-product γ-rays being achieved by means of a Cherenkov-type detector or a γ-scintillation counter. The difference between the energy spectra of the prompt γ-rays and those from longer-lived fission products is insufficiently marked to enable the two sources to be differentiated, except perhaps near full-power operation. In a swimming-pool reactor the Cherenkov radiation from fast electrons in the water round the core (arising from neutron-capture γ-rays in hydrogen), might be used for high-power-level measurements or for high-power trip controls.

In reply to Dr. Birks, scintillation counters certainly have a wide and useful field of application in nuclear physics, but there is a notable lack of suitable phosphors for slow-neutron detection over a wide range of flux levels and in the presence of high γ-radiation fields. Such counters have been considered for use in reactor-control applications and in most cases were discarded in favour of gas-ionization detectors. Dr. Birks's calculation that a 1 mm^3 scintillation crystal might be used in place of the RC/1 chamber is correct only in the sense that 1 mm^3 of a solid detection medium would have a total absorbing power for ionizing radiations equivalent to the gas in the ion chamber. He does not state how it is to be used as a neutron detector. The low limit of neutron flux at which a detector can be used is determined by the counting statistics, which depend on the amount neutron-absorbing material used in it. For example, 100 mg boron 10, which has a total thermal-neutron capture cross-secti of about 20 cm^2, would give rise to nearly 20 ionizing events p second in unit neutron flux, if used in a counter as large as t RC/1 chamber. If the detector were reduced in size the counti rate would be reduced, owing to increased self-shielding in t detector. In the limit when the detector has 100% absorpti efficiency for neutrons, the counting rate in unit flux will equal t physical cross-sectional area.

In order to achieve the highest possible n/γ discrimination either pulse-type or mean-level radiation detectors it is necessa to arrange that the absorption path length of the detecti medium (gas, liquid or solid) is of the same order of magnitude the range of the ionizing particles given off in the neutron reacti [e.g. (n, α) or n fission]. Full advantage is then taken of t difference in specific ionization between the highly ionizi α-particles or fission fragments and secondary electrons fro γ-ray interactions. These can easily be met in gas-ionizati detectors with path lengths in the gas of a few milligrams p square centimetre. The equivalent scintillation counter would a very thin sheet of phosphor with boron or fissile material other equivalent neutron-absorbing material incorporated in Zinc-sulphide borate-glass mixtures have been used in this wa but are at present inferior to gas counters in their n discrimination.

The properties of scintillation phosphors are seriously impair by radiation exposures as high as 10^6 rads, whereas ionization a fission chambers are not adversely affected by radiation dos of the order of 10^{10} rads. The most sensitive components in t gas counter are the insulators. They need only to be subject to γ-radiations and β-radiations from induced activities, where in a scintillation counter the phosphor is subjected to the mu higher radiation levels arising from the neutron reactions. T luminescence efficiency of scintillation phosphors has an appr ciable temperature coefficient at normal temperatures (abo 1% per deg C). At elevated temperatures (about 100° C) th performance deteriorates markedly. Thus the gas counter w have a longer operational life at high radiation levels and elevat temperatures than a scintillation counter.

There are special applications, particularly in the field epithermal neutron measurement, where a high-efficiency scint lation detector can be used with advantage, and there is need f the development of transparent phosphors containing boro lithium or fissile material. Lithium-iodide and lithium-bromi phosphors have been used, but their value as neutron detecto is limited by the high level of β-activity induced in iodine a bromine.

In reply to Mr. Weill, boron-coated thermopiles have be used for reactor-flux measurements, in particular for the measur ment of flux distribution in the core. The zero stability a calibration sensitivity of a thermal element of this kind a inevitably affected by changes in ambient temperature, a although these effects might be minimized by suitable desig they cannot be entirely eliminated. Some details of desig produced at the Atomic Energy Research Establishment a given elsewhere.* The range of measurement in a single desi is limited to about two decades and is restricted to flux leve greater than 10^{10} n/cm^2/sec. The time-constants are also lo (tens of seconds) compared with those of ionization chambe used at high flux levels. Neutron-sensitive thermopiles are value for flux-scanning applications, where it might not

* JAQUES, T. A. J., BALLINGER, H. A., and WADE, F.: 'Neutron Detectors Reactor Instrumentation', *Proceedings I.E.E.*, Paper No. 1433 R, December, 1 (100, Part I, p. 110).

possible to use high-insulation leads with an ion chamber, because of space considerations and accessibility.

Dr. Mitchell raises the question of a.c. operation of ionization chambers and points out the advantages to be gained by changing from d.c. to a.c. amplifiers. Some work on a.c. operation of ion chambers at comparatively low radiation levels has been reported.* A balanced bridge system is used to cancel out the reactive component of impedance due to the chamber capacitance. The resistive component is dependent on the amplitude and frequency of the applied alternating voltage and does not vary in a strictly linear manner with radiation intensity. The response of these devices is in general more directly dependent on ion mobilities and recombination effects than an ionization chamber used under d.c. saturation conditions, and is therefore likely to be more temperature-dependent. There is scope for further work in this field on both ion-chamber operation and on methods of measuring the a.c. admittance. The dependence on ion mobilities might be reduced by operating the chamber in such a way as to achieve 'd.c. saturation conditions' during a part of each cycle. This would entail increasing the amplitude of the applied voltage, with an increase in the relative value of the reactive component, but a useful compromise might be possible by a suitable choice of ionization densities and frequency of the applied a.c. power.

Mr. Smith suggests the use of a fission chamber to obtain an instrumental indication of fission-product power in a reactor. An auxiliary fission-chamber containing fissile material covered with a thin screen, which would absorb fission fragments but would allow fission-product β- and γ-radiations to be transmitted and measured, could be used to give an indication of fission-product power. Ideally, it would be necessary to use a detector capable of absorbing all the fission-product radiations, but an approximate indication could be obtained in a gas-ionization chamber measuring the specific ionization of the β-radiations. If the fission-power instrument were installed at the same time as the fuel it would give a measure of the subsequent fission power during operation and after shutting-down. Complications would arise, however, when fuel elements were redistributed and partial refuelling carried out. Fig. 1 in the paper by Messrs. Cox and Walker shows how the fission power depends on the period of operation and on the time after shutting-down. If changes were made in the core loading it would be necessary to make corresponding changes in the fission-power instrument if it were required to continue to simulate the core under all conditions. It might not be necessary to do this if it were only required to measure the working level of fission-product power, as this builds up to a saturation value in a period of a few days' irradiation. The decay of fission-product power after shutting-down, however, is more dependent on previous irradiation history. Mr. Smith's suggestion that it is appropriate to consider how far instrumentation in power reactors might be reduced is good. It is perhaps better to compute fission-product power from data given by existing instruments than to devise another measuring instrument.

Mr. Parr's statement that much of the complexity of reactor instrumentation is due to the nature of the primary elements is perhaps true of pulse-counting equipment. The equipment required for d.c. ionization chambers is relatively simple and reliable, and the output current available at high flux levels in a chamber of the RC/1 size ($\simeq 100\mu A$) is comparable with that obtainable from temperature-measuring thermocouples and bolometers. We are not aware of any radically new possibilities for instruments capable of giving greatly increased outputs and with a rapid response time.

* WARD, A. H.: 'Low-Frequency Operation of Balanced Ion Chambers in an A.C. Bridge', A.E.R.E. Harwell Report, 1953, No. EL/R 1107.

Mr. G. E. Lockett (*in reply*): In answer to Dr. Taylor, the mechanisms described in the Sections on the hydraulic accelerated shut-off mechanism and the combined-element drive unit have limited strokes and no appreciable increase in length is practicable. A number of detail features in the designs might well apply, however, in other types of long-stroke application.

The mechanism described in the Section on the shut-off-element operating head also has some limitation on its range of travel; an increase of three to four times the present figure is a probable limit and this would involve some variation in the winding drum and stop system. It has been convenient to use some of these units without internal modification on other critical assemblies using a differential pulley system to increase the stroke to about 5 ft. The total controlled energy is similar.

The statement that enclosure of motor drives within a pressure shell might make more problems than it solved is almost certainly true in a liquid-cooled reactor; however, in a gas-cooled reactor with a gas space above a liquid coolant, it might be possible to obtain a better solution by that method in preference to driving through a rotating gas seal. A number of design difficulties remain, and some of them have been mentioned by Mr. Stonehouse.

Dr. Taylor also asks how fuel loading is achieved in a system which moves fuel elements for control. If a vertical core arrangement is used, with fuel lowered in from above, loading might be effected in the same manner as for neighbouring fixed-fuel elements. This would generally require a carriage assembly running in guides and open at the top, the drive being taken vertically downward. Although that principle is simple, the detail engineering of cooling and guiding can be rather exacting.

Mr. Heath questions the Harwell policy of designing two types of mechanism when the better of the two designs could be used throughout; but the better design is not likely to be known until after a long period of operation; mechanisms have a habit of working perfectly under test conditions and leaving the surprise fault to occur during operation in the reactor. There is usually, however, some design justification for separate mechanisms, since shut-off elements and regulation elements require a number of basically different features and space might often be used to better advantage. Zeus is an example where alternate elements are driven from above and below.

Mr. Bowen states that the use of interlocking, to secure fool-proof operation, transfers the safety responsibility from the operator to the maintenance engineer. This is to some extent true, but should interlocks be omitted for that reason? Interlocks rely mainly on mechanical switches, which have proved to be amongst the more reliable parts of the equipment.

Mr. Bowen also comments that sequence operation of groups of elements is open to the same risk of parallel operation that paragraph (*h*) of the Section on design aims sought to avoid. Whilst this is true, the degree of risk is very much less and even if all sequence-interlocking were overridden, the effect of parallel movement of safety, shut-off and regulation elements would be to increase the intended maximum reactivity rate by a factor of three. Although this might be embarrassing it would not be disastrous.

Gravity-assisted shut-off is an obvious safety aim with a static reactor. This does not preclude the use of stored energy in some form to assist release. For propulsion reactors gravity assistance is still not ruled out, although additional design features are involved.

In a sliding-seal drive through a pressure shell, mechanical failure will blow the sliding member outwards, but this is not necessarily an unsafe direction, e.g. if fuel elements are being moved for control. In any control drive it is the designer's duty to ensure that failure is not unsafe.

Mr. Stonehouse suggests that an accuracy of indication of $\rho = 10^{-5}$ is unnecessarily fine for a power reactor. The paper actually states that the accuracy does not need to be finer than this figure; it could, in fact, be a good deal coarser. The differential expansion of reactor members might well decide the limiting accuracy that can be obtained. In any case, an absolute measurement is not required, the physicist being normally interested in relative movement.

Although in general accord with Mr. Stonehouse on th problems of driving members within the pressure shell, I believ that dry rolling bearings will give a more reliable solution whe conventional lubrication is ruled out and rotational speeds a not high. For higher speeds—and this might include mot shafts—the gas bearing might be worth considering, and althou it does not lend itself so readily to intermittent running, sati factory results are obtained with lightly loaded systems.

DISCUSSION ON 'INTENSIFICATION OF THE X-RAY IMAGE IN INDUSTRIAL RADIOLOGY'*

NORTH-WESTERN UTILIZATION GROUP AT MANCHESTER, 31ST JANUARY, 1956

Mr. J. R. Smith: The main interest of such bodies as the leading engineering insurance companies in this particular field lies in equipment which may be used for site investigation of known or suspected defects in boilers or pressure vessels. Magnetic crack-detector application generally entails rivet removal where riveted seams are concerned, and the organization with which I am associated has developed the use of ultrasonic flaw-detection apparatus as a reliable form of non-destructive test. Portable γ-ray equipment has, in our experience, been successfully used in site investigations of suspectedly defective seams of water-tube boiler drums on site, but this method calls for special setting up and very careful handling of the γ-ray source, necessarily resulting in slowness and consequently lack of economical operation.

Might it be hoped that a commercial development of the fluoroscopic image intensifier described will become available for use in site investigations, thus providing a quick and economical means of scanning, say, the longitudinal seams of boiler drums for defects? From the paper, the difficulties would appear to lie in the limited penetrative powers of the equipment and, possibly, the protection of operators against the effects of radiation. The authors' description of a long tube being moved longitudinally across the X-ray source inspires belief in the feasibility of so arranging matters that the equipment is moved along the subject of investigation.

Mr. C. A. M. Thornton: Would the X-ray image-intensifier tube assist in the detection of radial cracks in high-pressure steel tubing? This tubing is made in lengths of 12ft or more, and we are concerned with diameters up to 2¼in, the bore being about half of this. Some consignments have been found to contain radial cracks which are not easy to detect by some other methods, in that they may penetrate neither to the inside nor to the outside of the tube. A reliable method of detection of a few cracks in a large quantity of tubing is required. Slow and laborious methods are of little use in this problem.

Mr. J. Tozer: It would appear that the intensification gained by the methods proposed in the paper will tend to show all the minor discrepancies in a material being examined. One wonders whether this will result in quantities of materials being rejected for unimportant defects.

The authors indicate that great advantages can be obtained by the use of fluoroscopy and that this application is assisted by slow movement of the object being examined, particularly for crack detection. How large an object can be examined by this method with the equipment already produced, and what suggestions can be made for the examination of objects having a awkward shape?

Mr. J. N. M. Legate: Is any difficulty experienced in practi due to loss of focus and consequent deterioration of definitio due to supply variation? I take it that the intensifier tube wou often be used in fabrication shops and similar circumstance where heavy transient fluctuations might be experienced, owin for example, to welding loads on the supply; under such circur stances, is there any necessity for special stabilizing arrangemen for the input to the tube?

Dr. A. Nemet and **Mr. W. F. Cox** (*in reply*): In answer to M Smith, the application of the image intensifier in the steel-pi factory is, to our knowledge, the first example of its use for lar objects. There is no reason why the tube should not be used f site investigation, although the handling equipment will have be more flexible and mobile.

For the present tube with the associated 150kV X-ray equi ment, the maximum penetration claimed is 30mm of steel. F increased thicknesses, the voltage would have to be increase and thus the X-ray equipment would have to be larger; this, turn, is bound to reduce its mobility and flexibility, especial since the protective screen would also have to be heavier. special cases, closed-circuit television may be applied.

The detection of radial cracks in 2¼in steel tube, mention by Mr. Thornton, is probably possible with the present equi ment. The small diameter of the tubes would allow hi brightness to be obtained by placing the X-ray tube and t intensifier close together. The uniformity of the object wou seem to allow a straightforward solution of the handling questio and thus permit relatively speedy operation. The radial alig ment of the cracks should greatly help in their detection. T ultimate detection will, of course, depend on the width and dep of the cracks. Protection would present no particular difficulti in this case.

Mr. Tozer suggests that the improved sensitivity of t intensifier may cause materials with unimportant defects to rejected. This problem does not appear to us to be serious X-ray examinations, and it arises more in ultrasonic work. T question applies to ordinary radiography more than to imag intensifier work because of the higher sensitivity of the former.

The apparatus already produced is suitable for small objec or laboratory use, and suitable handling equipment will have be developed for larger objects and those having an awkwa shape.

In answer to Mr. Legate, the focus, and thus the definition the tube, is unaffected by mains voltage variation.

* NEMET, A., and COX, W. F.: Paper No. 1881 U, July 1955 (see 103 B, p. 345).

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Paper No. 2131
Sept. 1956

SERVO-OPERATED RECORDING INSTRUMENTS

A Review of Progress.

By A. J. MADDOCK, D.Sc., F.Inst.P., Member.

SUMMARY

Commencing with the first self-balancing bridge or potentiometer devised in 1897, a review is given, in historical form, of the several types of servo-operated recording instruments that have been devised since that date. These recorders are all of the type in which a correcting action takes place in the instrument itself, thus making available considerably more power for the recording stylus or pen than is available in direct-acting instruments. A more detailed discussion is then given of the principal types of modern instruments, classified according to the circuit component which is varied to produce balance, namely resistor or potentiometer, capacitor, electromagnetic device. Most instruments record against time as one of the variables, but function plotters, in which the relation between two variables other than time is plotted, are discussed, as also are scanning recorders devised for recording from a large number of input points. Several other special types are also included.

(1) INTRODUCTION

It seems advisable, at the commencement of this review, to define what types of instrument are intended to be covered by the title. By 'servo-operated recorders' is meant those recorders which are electrical in nature and in which the final recording means is not operated directly by the input signal but through the intermediary of some power-amplifying system, so that greater power is available at the point of recording. In practically all cases the servo system employed is of the closed-loop type whereby feedback is introduced into the system so that input and output are compared, any deviation between them actuating the recording system and, at the same time, operating an appropriate control to maintain the system in a state of balance.

Whilst the instruments to be described are electrically operated and require an electrical input signal for their operation, they may be used for recording non-electrical quantities such as temperature, pressure, flow, level, strain, displacement, pH and many others[35] provided that a suitable transducer is employed to convert the physical, chemical or mechanical property to an electrical signal bearing a unique relation to it. Many such convertors are available, and it is not considered to be within the scope of this review to describe them. Fundamentally, therefore, by the use of an appropriate transducer the electrical recorder is of wide applicability and the same instrument can be used for a multiplicity of purposes without serious modification.

As in other types of graphical recorder, recording may be by means of ink on paper, stylus on prepared paper (for pressure- or heat-sensitive recording), electrolytic action on special paper or other method. Ink on paper is the most popular. As none of these is applicable only to servo-operated recorders no further detail will be entered into here. In some of the descriptions to be given later the recording method appropriate to a particular type may, however, be quoted. Since the chart-driving mechanism is the same as that employed in direct-writing recorders no further description is necessary; suffice it to say that in practically all cases synchronous-type clock motors operated from the a.c. mains are used and that the gear ratios and chart-driving systems all follow standard practice.

In the following subsection the advantages possessed by servo-operated recorders, particularly those of the continuously balancing type, are listed. Following this, in Section 2, brief particulars of the general principles of several recorders are given, arranged in historical order; subsequent Sections select the more generally used types of modern instrument for description in more detail. Since the majority of applications involve the recording of one variable against time, this class of recorder is given most notice, but co-ordinate plotters for two (electrical) variables are also dealt with.

(1.1) Principal Features of Continuous-Balance Recorders

Servo-operated recorders in their modern guise of the continuously balancing type have the following general characteristics:

(*a*) Ample power is available for operating the recording mechanism.
(*b*) Rectilinear, equispaced co-ordinates are produced.
(*c*) Wide charts can be used.
(*d*) General accuracy is high.
(*e*) Owing to the large power amplification available the sensitivity is high.
(*f*) Speed of recording is high, so that records from a multiplicity of sources become practicable with a relatively short repetition time.
(*g*) The recorder is always operating as a null-balance instrument and is continuously operative; it therefore follows changes in the input variable directly.
(*h*) If the null-balance principle is used variations of supply voltage or changes in gain of the amplifier do not affect the balance point and hence the indicated reading.
(*i*) Recording is not limited to one variable against time, the latter being provided by the usual clock-driven mechanism for the chart: a similar servo system and amplifier can be arranged to drive the chart (or complete pen guide) in response to a second input variable so that direct plotting of one variable against another is possible.
(*j*) Extension of such a recorder to that of controller as well is possible.
(*k*) They are insensitive to mechanical shocks and vibration.
(*l*) As with other types of electrical recorder, recording can take place at a considerable distance from the sensing element.

(2) HISTORICAL

One tends to think of a continuously self-balancing potentiometer recorder as a fairly recent innovation which has come into much prominence since the last war. Whilst modern developments in servo techniques have certainly produced vastly improved and rapid recorders of this type, the basic idea dates back to 1897;* the term 'servo system' was not, of course, in use at that time.

The earliest recorder of this type was invented by Prof. H. L. Callendar (Fig. 1).[1,2,3,4] A schematic of the arrangement he adopted is shown in Fig. 2. A contact-making galvanometer, connected as the null-detecting instrument in a Wheatstone bridge or potentiometer circuit, brought into action relays for releasing the driving mechanism of the pen and, at the same time, altered the control in the operating circuit to restore equilibrium. The boom of the moving-coil galvanometer carried two insulated wires ending in a fork on either side of a fixed

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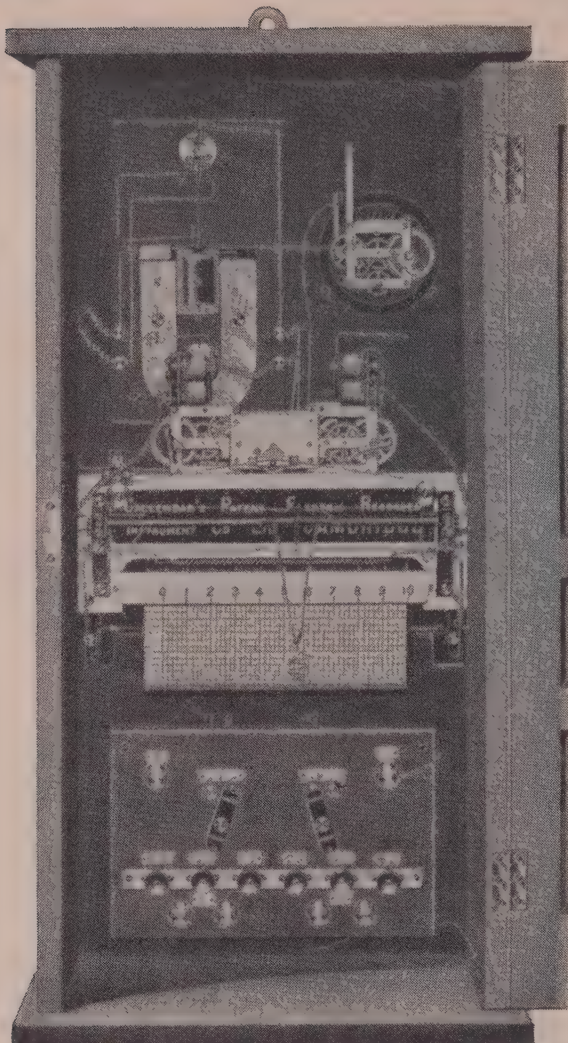
* The idea was first tried out by Prof. Callendar in 1886, but he was unable to procure or devise a relay sensitive enough to make the system work.



[*Cambridge Instrument Co., Ltd.*

Fig. 1—Callendar's relay recorder, 1897.

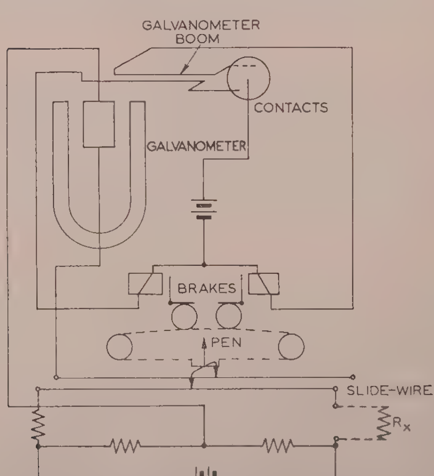


Fig. 2.—Schematic of Callendar's relay recorder.

contact wheel; the ends of the wires were tipped with platinu or silver foil and the contact wheel had a platinum rim. T relay armatures acted as brakes on two separate clockwo mechanisms. Whichever relay was energized released the bra on the mechanism and allowed the sliding contact on the potenti meter or bridge to move in the appropriate direction to resto the circuit to balance; the slider also carried the pen for recordi on the usual paper chart. The major difficulty in the use of t instrument—and in others operating on similar principles—w in ensuring good contact between the moving and fixed contac and to this end the fixed contact was made in wheel form so th it could be rotated slowly past scrapers and thus keep presenting a fresh surface to the moving contacts.

Shortly after this (about 1899) V. Arcioni devised[1,2,5] a syste in which the current to the balancing-motor armature w switched directly by the galvanometer contacts. Fig. 3 sho

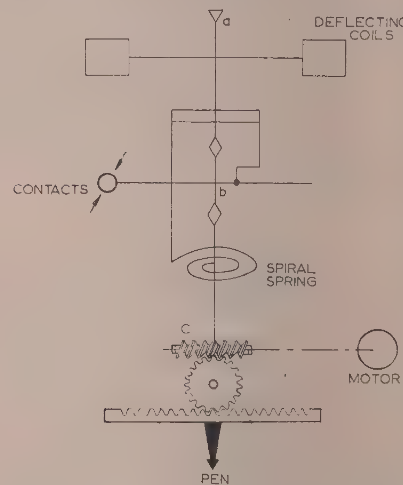


Fig. 3.—General principles of Arcioni's recorder.

that there were three shafts in line but separated and ind pendently pivoted. The first (*a*) carried the deflecting coils the galvanometer system, the second (*b*) carried a contact ar connected to (*a*) by a link system, and the third (*c*) was driv by the operating motor and connected to (*a*) by means of a spir spring and vertical pin; the motor also drove the pen on carriage through a rack and pinion. When the coils deflecte one contact was made and the motor operated until the spir spring balanced the deflecting torque, the contact was brok and the motor then stopped. This system did not balance potentiometer or bridge but varied the controlling torque of t direct-acting deflectional galvanometer. The motor was of t simple disc type with the field system continuously excited an the armature current switched by the contacts.

In 1905 a relay recorder,[1,2,5,6] as these instruments we then called, in which the sensitive element was a Kelvin curre balance, was produced in the United States. Instruments this type were made for many years in that country and also Italy.[5,6] The beam of the balance made contact with one other of two fixed contacts, switching directly to the field co of a split-field d.c. motor. The motor drove a lead-screw whi carried the pen arm: a special link system was arranged betwe the pen and the armature of the balance system. This instrume was used particularly for heavy currents (10 000–20 000 A) b also as a recording voltmeter or wattmeter; the wattmeter cou be converted to a watt-hour meter (with cyclometer dial ind cation) through the addition of an integrating-disc drive, driv

y the motor, with the position of the contacting wheel controlled om the pen carriage.

Another and later relay recorder[2,5] was produced in this ountry, in 1920 (Fig. 4). The diagram is almost self-

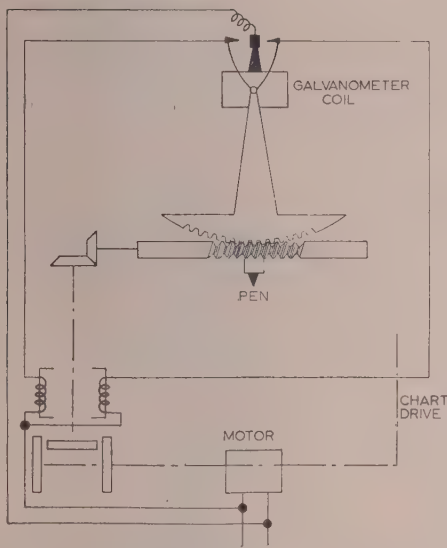


Fig. 4.—General principles of a British relay recorder.

explanatory, but the single moving contact of the galvanometer and the two 'fixed' contacts moved by the pen carriage may be noted. The contacts operated relays to engage the pen drive with one or other of two wheels driven continuously by the motor, so that the appropriate direction of rotation was obtained; the same motor drove the chart along the time axis so that chart speed and pen speed were interlinked—an unusual feature.

Mention has already been made of the difficulties encountered with contacts on these early instruments, and it is not surprising that other means were sought to eliminate them. A great step forward was made in 1909 when M. E. Leeds[7] filed a patent application in the United States (there were 67 claims in this patent!) for a 'step-by-step' recorder whereby a mechanical linkage was devised between the galvanometer movement, the pen carriage and the slide-wire contact; minor modifications were made in some of the details and the system mentioned below is that used in the later models. A galvanometer is used as the detecting element to sense when deviations occur from the balance condition. At short intervals the galvanometer needle is clamped. A pair of fingers then closes on the needle in its off-centre position and, by means of a clutch mechanism, enables the slide-wire to be rotated to bring the circuit towards balance; the recording pen is driven from the shaft of the slide-wire. Movements of the clamp, fingers, clutch, and slide-wire and pen are all controlled by a continuously running motor from which all the power is derived, the galvanometer merely acting as a positioning device to control the movement of the slide-wire system.

These electro-mechanical types of servo-operated recorders, as they may be called, have enjoyed immense popularity in one form or another since they became commercially available in 1911, and they are, of course, still in use. Since balancing is carried out in a series of steps occupying a definite time, they lack the ability to maintain themselves in continuous balance; therefore they are not able to follow a rapidly changing input signal, and this also means that for multi-point recording the time cycle is comparatively long.

The well-known Neuman audio-level recorder devised by von Braunmühl and Weber[8] in 1935 is used only with alternating signals, and any deviation from a fixed level at the output brings into action an ingenious clutch system associated with a continuously running motor. This controls the motion of a slider contact on the input potentiometer and also of the recording stylus.

Relay control of the motor was also adopted, about 1936, by Fairchild and Parsegian,[9] but to avoid contacts on the galvanometer they used a photocell to 'watch' any departures from the balance position. These authors worked out criteria for avoiding hunting, and although their first model required 20 sec to cover the 10 in chart-width, a later version reduced this to 2 sec.

By the 1930–40 decade electronic techniques were well advanced and 2-phase induction motors were available in the form required for instrument use. Efforts were therefore turned again towards developing continuous-balance potentiometer recorders using the new techniques available. The basis of all these is similar in that the out-of-balance voltage from the potentiometer or bridge circuit is amplified electronically and the amplifier output is applied directly to the motor which drives the system to the balance point. As the motor is then receiving no signal the system comes to rest and will remain in that condition until further deviations occur in the input. The whole is therefore continually operative; it can proceed over the full scale span in under 2 sec, and there are no movements so long as there is no change in the magnitude being measured. A sort of half-way stage was evolved in 1931, soon after hot-cathode thyratrons became available, by an American company,[2,10] which applied them as control elements for a d.c. controlling motor. A microphone was used to convert the d.c. input to alternating current, thus eliminating the galvanometer, or its like, for the first time.

A review up to 1935 is given in Reference 2 with some of the variations introduced by other manufacturers and not covered here.

The modern continuous-balance recorder, operating on the general lines outlined above, is due to Geyger and Keinath[11] in Germany (1938) and to Harrison, Wills and Side[12,13] in the United States (1941). Geyger and Keinath used the method for balancing an a.c. potentiometer, so that a straightforward a.c. amplifier could be used. Their work was concerned with determining changes in the capacitance and loss factor of insulating materials. For this, two a.c. potentiometers were balanced independently. The circuit diagram of this recorder, which is interesting especially because in-phase and quadrature components enter into it, is given in Fig. 5; it is generally self-explanatory. The United States workers were concerned with a more universal use, particularly for temperature measurements

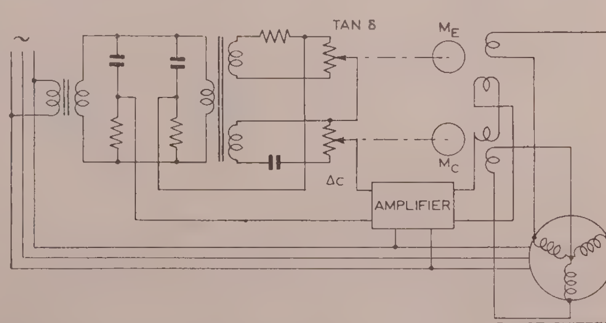


Fig. 5.—Schematic of automatic a.c. potentiometer of Geyger and Keinath.

involving thermocouples. Since both input and potentiometer output are in the form of direct current, the difficulties inherent in direct-coupled d.c. amplifiers were avoided by adopting the chopper type of amplifier, in which the d.c. input is interrupted by means of a reed vibrating between two fixed contacts;[36] an a.c. amplifier can then be used (Fig. 6). They made a significant advance in the mechanical construction of the vibrator, and a large number of modern recorders made by several manufacturers all follow this plan.[10, 14, 15, 16] A few, however, utilize clutch mechanisms, particularly for the highest speeds of traverse.

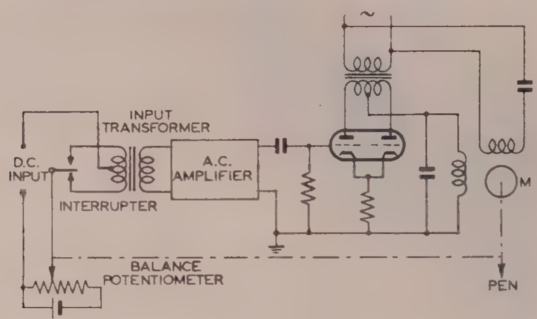


Fig. 6.—Schematic of d.c. self-balancing potentiometer of Harrison, Wills and Side.

A balanced a.c. bridge using a variable capacitor in place of the more usual resistor[17] appeared in 1943, and it was claimed for it that the effective control was quite stepless. A version suitable for use with d.c. input followed some years later and in this a vibrator is required for switching capacitors.

Whilst most recorders use time as one axis and drive the cl by a synchronous clock, a logical development can be made the continuous-balance recorders to enable them to plot any related variables—to become, in fact, co-ordinate plotters x-y plotters, as they have been called. The necessary chang accomplished by providing a completely separate servo sys to move the chart (or complete pen guide) backwards and wards in accordance with, say, the x-co-ordinate, whilst the us pen gives the necessary movement for the y-co-ordinate. T was suggested by Behar[18] in 1940, but commercial models did become available until 10 years later.

To provide more rapid recording or more data on a gi chart size, Keinath has devised a sweep-balance recorder.[19] this the full range of voltage provided by a potentiometer scanned periodically by the slider contact making excursi along it; the marker stylus travels with it. Whenever contact passes through the point of electrical balance electronic relay triggers the marking circuit to print a point the chart. Several variations of this were described by Keina and some application has been made by other workers, as far as is known no commercial model operates on th principles.

More details of the modern versions of the recorders h noted briefly are given in Section 3 onwards. Table 1 is historical summary of the progress described above, listing t most outstanding developments.

Table 1

Historical Summary of Developments in Servo-Operated Recorders

Date of availability	Originator	No.	Main features	Mentioned in Section	Reference in Section 14
1897	H. L. Callendar	1	Galvanometer with contacts operates clutches associated with motor	2	1, 2, 3, 4
1899	V. Arcioni	2	Torque-balance unit with contacts switches motor current	2	1, 2, 5
1905		3	Kelvin current balance with contacts switches motor current. Improved versions in use about 1929	2	1, 2, 5, 6
1911	M. E. Leeds	4	Mechanical feelers, associated with clutch, sense position of galvanometer needle	2 and 3	2, 7
1931		5	Continuous-balance potentiometer and d.c.-to-a.c. convertor	2	2, 10
1935	H. J. v. Braunmühl and W. Weber	6	Special clutch device selects direction of motion of pen and contact on logarithmic potentiometer	2 and 8	8
1936	C. O. Fairchild and V. L. Parsegian	7	Galvanometer-photocell combination. Relays switch motor current	2 and 7	9
1938	G. Keinath and W. Geyger	8	Continuous-balance system for a.c. bridge. Two-phase induction motor	2	11
1941	T. R. Harrison, W. P. Willis and F. W. Side	9	Continuous-balance potentiometer. D.C.-to-a.c. conversion by 'chopper'. Two-phase induction motor. This and No. 8 were forerunners of all modern recorders of this type	2 and 4	12, 13
1943		10	Balancing capacitor in a.c. bridge operated by double solenoid system	2 and 5	17
From about 1945 to 1950		11	Present-day continuous-balance potentiometer and bridge recorders, operating essentially on same principle as one form of No. 9	2 and 4	4, 10, 14, 15
1946	G. Keinath	12	Full range of potentiometer voltage scanned periodically and balance point recorded	10	19
1950	M. F. Behar (by suggestion in 1940)	13	Co-ordinate plotters. Two separate systems for related inputs	9	(18)
1954		14	Convertor uses Hall effect. Secondary electromagnetic balancing circuit	6	

(3) ELECTRO-MECHANICAL SERVO RECORDERS (STEP-BY-STEP)

As noted in the introduction, this type of recorder[7] held t field for about 30 years and large numbers are to-day, and w

ontinue to be, in use. Whilst a galvanometer is used as the ele-ient sensing any out-of-balance in the electrical circuit, the novement required of this instrument is very limited. Thus the alvanometer can be somewhat more robust than usual whilst ill retaining sufficient sensitivity at the balance point. Every ew seconds the galvanometer needle is clamped, and for this eason the movement is of the suspended type to allow for the light tilting motion during clamping.

The action of a typical instrument may be understood from Fig. 7, which is a diagrammatic representation of the complete

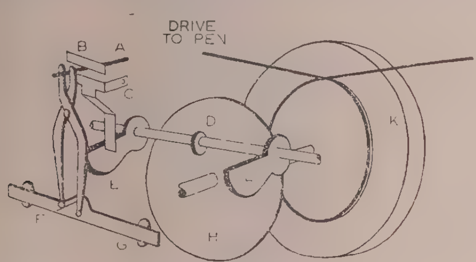


Fig. 7.—Exploded view of operating mechanism of the Leeds electro-mechanical recorder.

nechanical system for operating the balancing potentio-neter. At regular intervals of time—normally about 2 sec—the galvanometer needle A is clamped between a fixed member B ind a member C which is moved vertically by a cam D driven by a continuously running motor. Cams then operate the two ingers of a scissors movement so that they close upon the clamped galvanometer needle. If the needle is in the central null) position both fingers reach the centre of the system and no further action ensues, but if the needle has been deflected to one side one finger will be prevented from moving towards the centre whilst the other will travel past the centre until it, too, ouches the needle. In so doing the lower portion of the scissors noves the peg F to one side and allows the light clutch-bar G o tilt in a direction depending upon which finger had to travel he farthest from its rest position; the angle that the bar G has urned through is thus directly proportional to the angle of leviation of the galvanometer needle. Facing the clutch-bar G, which carries two pads at its extremities, is a clutch-plate H nounted on the axis of the slide-wire disc K, and as soon as the cissors have finished their movement the bar G is engaged with he plate H, again by the operating motor. The next operation n the sequence is for the two control cams L to be rotated by the notor, when one of them will operate against the end of the lutch-bar and bring it back to the horizontal position; in this operation the slide-wire disc will also be rotated through the ame angle as that through which the bar has been deviated. Finally, the scissors return to their fully open position, the alvanometer is unclamped and the system is ready for the ext cycle.

There are no contacts to be made in this system, and the alvanometer can be quite sensitive and swing freely under ormal conditions, but when clamped the needle acts as a nechanical stop for the sensing fingers. The power to operate he fingers, to rotate the clutch-bar, to drive the slide-wire round nd to move the pen carriage is all derived from the operating lectric motor. The circuit is so connected, of course, that the novement of the slide-wire disc is in the direction to bring the ystem nearer to balance. The pen carriage is driven by a flexible vire attached to the slide-wire disc and thus moves in linear nd regular motion across the width of the chart.

It will be appreciated that if out-of-balance occurs the return to balanced conditions takes place in a step-by-step fashion with the slide-wire moved in corresponding steps with decreasing amplitude but at the regular intervals of 2 sec imposed by the timing mechanism; the response to a step-function change in input is therefore somewhat as shown diagrammatically in Fig. 8.

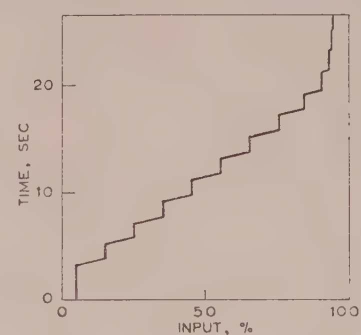


Fig. 8.—Response to a step function in a step-by-step recorder.

The time taken to cover a 10 in-wide chart might therefore be about 20 sec. Multi-point recording—e.g. of the temperatures at a number of points—can be carried out with the several inputs connected to the one recorder in sequence by an electrically operated switch and with the pen system simultaneously changing in colour or printed number to give identification on the scale. With a cycling time of 2 sec and allowing an average of 10 sec for each balancing operation it is seen that the repetition time for sampling the various input points will be of the order of one minute or more for six points.

The sensitivity of the galvanometer sets a lower limit to the span of the scale, and this amounts to about 5 mV.

(4) CONTINUOUS BALANCE RECORDERS: POTENTIOMETER AND RESISTANCE-VARIATION TYPES

(4.1) General Principles

The modern continuous-balance recorder operates on a very simple principle, but it has needed advances in three fields to bring about the integrated whole. These are: (*a*) an understanding of the principles of servo-operation, particularly as applied to electrical servos, (*b*) improvements in servo-operating motors and feedback generators, and (*c*) improvements in methods of d.c. amplification.

The out-of-balance potential from a potentiometer or Wheatstone-bridge circuit is amplified electronically to a sufficient level to operate a motor which drives the slide-wire contact towards the point of balance. When balance occurs there is no current to the motor and the system comes to rest; any further deviation from balance causes corrective action to follow. The system is thus always in a state of readiness to detect the smallest changes and to bring the circuit back to balance very quickly; full-scale deflection requires only one or two seconds.

The potentiometer circuit is used when direct potentials or currents are being recorded, e.g. with thermocouples, pH electrodes or photocells, and the bridge circuit when variations of resistance are being recorded, e.g. with resistance thermometers or strain gauges; with the bridge circuit either d.c. or a.c. polarization may be employed. Cases where alternating potentials are to be recorded are relatively infrequent and so all present-day recorders use d.c. potentiometers only; when a.c. input is necessary (other than in the bridge circuit) a thermal converter is interposed between source and recorder to convert

Table 2.—COMPARATIVE DATA ON SELF-BALANCING POTENTIOMETER RECORDERS BALANCED DIRECTLY BY NULL VOLTAGE FROM RESISTANCE NETWORK

	Make of instrument							
	A	B	C1	C2	D	E	F	G
Scale span, mV	0–5 0–10 up to 0–40	0–0·5 up to 0–50	0–1 up to 0–60	0–1	0–8	0–5	0–1 up to 0–10	0–0·1 up to 0–100
Error, %	0·25	0·5	0·5	0·5	0·25	0·25	0·38	0·3
Sensitivity, %	0·17	0·2	0·1	0·1		0·1	0·07	0·1
Full-scale response time, sec	5	2 (1 in some cases)	2	0·5	8	1	2 (1 in some cases)	1–4
Chart width, in	10	10	7·1	7·1	8	9·8	11	10
Chart speeds, in/h	1–480	1–60	½–120	7·5–360	0·6–2·4	0·8–95	6–120	½–3600
Number of recordings possible	1–6 separate pens Dot for 2–6	1–16 Dot for 2–16	1–6 Dot for 2–6	1–6 Dot for 2–6	1–6 Dot for 2–6	1–12 Dot for 2–12	1–16 Dot for 2–24	1–24 Dot for 2–24
Potentiometer supply	1½ V dry cell	1½ V dry cell	1½ V dry cell or stabilized d.c. from mains		Stabilized d.c. from mains	Stabilized d.c. from mains		Dry cell
Bridge supply	A.C. 4 mA	A.C.				12 V a.c. 1 mA		
Standardizing period	½ h	¼ h (1 h for multi-point printing)	Manually	Manually	Manually occasionally	Manually once a month	1/6 h	¾ h
Standardizing means	Separate motor	Main motor	Hand	Hand	Hand	Hand	Main motor	Main motor
Amplifier type and gain	3-stage p–p; 30 000	4-stage s–s; 10^7 for 0·5 mV span	5-stage s–s	4-stage s–s				4-stage s–s (5 for lowest input); 10^6
Maximum source impedance, ohms	10 for 5 mV	100 for 0·5 mV 1 000 for 5 mV and above	300 for 1 mV	1 000				Several hundred
Slide-wire resistance, ohms	6					1 000	1 600	
Slide-wire turns and type	300 (4 contacts) linear	Linear	Circular			1 300 Linear	Helical	Circular
Mounting style	Panel	Panel	Panel	Panel	Panel	Panel	Panel	Panel
Special features	Slide-wire oil-immersed		Slide-wire oil-immersed	Clutch system with main motor in continuous rotation	Also made with circular chart		Also made with circular chart 12 in diameter	

s–s = single-sided p–p = push–pull

the input to direct current. At first sight this may seem a comp cated method, since the recorder promptly converts this back alternating current to feed it into the amplifier and thence to t correcting motor. However, an a.c. potentiometer would be more complicated arrangement and would require two balanci systems, one for the in-phase and another for the quadratu component. It is not impossible to design a system on the lines, and in fact the early continuous-balance recorder Keinath and Geyger[11] operated on just this principle and w the first one to use a 2-phase motor for driving the slide-wi contact (see Fig. 5).

Many manufacturers now make recorders of this nature; operate on very much the same principle and have similar ma characteristics. A comparison of the properties of a number recorders of different makes is given in Table 2.

The basic circuit shown in Fig. 9A is for use as an automat potentiometer for recording d.c. inputs, and that shown

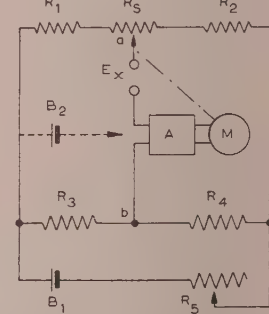


Fig. 9A.—Basic circuit of self-balancing potentiometer.

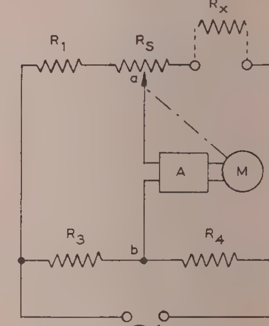


Fig. 9B.—Basic circuit of self-balancing Wheatstone bridge.

Fig. 9B is for using resistance variations in a Wheatstone-brid circuit. Even with the potentiometer the circuit is often arrange in bridge form, as in Fig. 9A; the function of the addition resistors will be described later. The external e.m.f. is applie at E_x to the diagonal of the bridge and in series with the amplifi feeding the servo motor. The circuit sets itself to give ze potential difference between points (a) and (b) when it is cle that the potentiometer voltage is equal to the input voltage. A deviation of input voltage from an initial balance point caus the amplified output signal to drive the motor in such a sense to move the contact on the slide-wire R_s to cancel out th potential and, at the same time, to move the pen carriage alo by a corresponding amount. Current for the circuit is provid

y the source B_1 through the variable resistor R_5. Since a onstant current is desired in the potentiometer, some means of hecking the constancy from time to time is necessary; this is rovided by checking against a standard cell (B_2) which is switched either by hand or automatically with the normal input signal isconnected. The system then adjusts the rheostat R_5 until alance is obtained, when the connections revert to the normal ecording arrangement. Such standardizing procedure is ormally arranged to be carried out automatically at, say, hourly r half-hourly intervals, the chart-driving motor effecting the ecessary switching operations and at the same time uncoupling e servo-motor from the slide-wire contact but connecting it to rive R_5, by means of a clutch; some makers use an entirely eparate motor for driving this adjusting rheostat. Although he standard cell B_2 is shown in Fig. 9A as backing off part (or all) f the bridge voltage, another arrangement is sometimes adopted n which it backs off the voltage developed across a standard esistor in the current supply to the bridge, i.e. in series with R_5.

Resistors R_1, R_2, R_3 and R_4 permit adjustment of the scale pan that is to be covered by the movement of the slide-wire ontact. Since the whole width of the recorder chart is covered y the slide-wire, the actual span, in millivolts, can be varied coneniently by suitable choice of these resistors, and a scale either tarting at zero or set up from zero may be used as desired. One of the main objects in forming a bridge by the addition of he two resistors R_3, R_4 is to enable a true zero for the system o be obtained without the slide-wire contact travelling exactly o the end of the slide-wire. A further use can be made of esistor R_3 (and sometimes of R_2 as well) in providing automatic old-junction compensation when a thermocouple is being used s the input device. The resistor is then wound of copper or ickel in order to have a larger temperature coefficient than all he other resistors, which are made of manganin, so that compensation for any ambient temperature variations is obtained. f the temperature variations were likely to be large the compensating resistor R_3 would be mounted externally near to the hermocouple head itself.

The bridge connection used in the potentiometer arrangement lso permits the instrument to be changed readily into a Wheatstone-bridge circuit for recording changes of resistance, nd the basic circuit for this is shown in Fig. 9B, R_x being the xternal resistance under measurement. For this arrangement onstant bridge voltage is not required, and so the whole unit nay be fed from an unstabilized supply. The supply may indeed e alternating, which is possible because the bridge supply is derived from the same source as that for the reference phase of he servo motor, and hence balancing of the bridge becomes a natter involving amplitude only. In this case, the a.c. out-ofbalance signal may be fed directly to the a.c. amplifier without he use of the vibrator as used for inverting d.c. inputs. Whilst some manufacturers only supply instruments for covering one unction (i.e. for use as a d.c. potentiometer or for use as an a.c. bridge), others supply standard instruments with link connections nabling the change-over to be effected by the user if desired.

In one special recorder devised[33] for achieving a threefold mplification of scale length, the electrical balancing circuit covers range three times that determined by the chart. The balancing notor drives an endless belt on which three styli are mounted, he width of the chart apart; thus as one stylus moves off the dge of the chart the next one takes over at the zero line, and the hird likewise takes over from the second.

(4.2) Electrical Details

The general accuracy of this class of recorder is of a high rder compared with normal graphic recorders, the error being bout 0·25% of full-scale span. Careful design is therefore required, notably in the resistors making up the bridge circuit and in the mechanical construction of the moving parts.

In several designs, the slide-wire itself, on which linearity and sensitivity will depend, consists of a single-layer helix about 11 in long, wound, with turns touching, on a cylindrical rod of ceramic or anodized aluminium alloy. In one instrument the slide-wire is mounted in a trough of oil to ensure efficient and reliable contact and the occlusion of dust. Other instruments have a circular disc with the slide-wire arranged in a groove instead of the linear system described above, and again one of these is mounted in oil. Yet another has the helical winding coiled around a drum.

Whichever system is used, sufficient turns must be provided on the slide-wire to ensure that the voltage step between turns is less than the minimum detectable voltage, or the minimum required to be recorded. Since this is usually 0·1% of the scale span, at least 1 000 turns are required. With a single contact 1 300 to 1 600 turns are general. Another arrangement is to use four contacts disposed around the helix, so that discrimination effectively down to one-quarter turn is possible, and then 300 turns are sufficient; this technique enables a shorter wire, of lower resistance, to be used. A parallel resistor of higher value is often provided across the slide-wire to enable the equivalent resistance to be brought to an exact value.

For general stability in the amplifier, an a.c. type is used with an inverter preceding it to convert the d.c. input signals. The inverter is of the vibrator type operating at mains frequency, usually with a single moving contact to change over between two fixed contacts, which are connected to opposite ends of an input transformer as shown in Fig. 6; some considerable step-up (10–20 times) can be effected here. This type of vibrator, when designed especially for d.c.-amplifier use, will operate at noise levels below a few microvolts so that full-scale spans for the recorder of 500μV and over are possible; more often they are in the millivolt region with a scale span of 1–10 mV.

Three- or four-stage amplifiers of conventional type (either single-sided or push-pull) will produce the necessary power of 6–10 watts for the servo motor, and it is often arranged that for large out-of-balance signals the amplifier shall reach saturation and so provide full output to the motor, dropping proportionately as the system comes nearer to the balance position (Fig. 10).

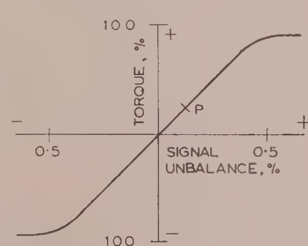


Fig. 10.—Typical curve of torque of balancing motor against input unbalance.

Minimum resolvable signal at point P (equal to sensitivity of instrument) produces ample torque to start motor under load.

The gain required of the amplifier depends, of course, on the scale span to be covered, but typical values are between 30 000 for several millivolts and 10^6 for fractions of a millivolt.

The servo motor used is of the 2-phase induction type with squirrel-cage rotor, one phase being fed from the amplifier whilst the reference phase is continuously excited from the mains supply. Motors with high torque/inertia ratio obviously aid in obtaining rapid response. To prevent hunting and overshoot of the system and yet permit high speeds of travel for the pen carriage, some

stabilizing system is required. In one method a tacho-generator, also of the 2-phase induction type with cup rotor, is directly driven by the motor and generates a voltage proportional to speed. This voltage is fed into the amplifier to provide a stabilizing signal, which falls to zero as the motor comes to rest. Another method is to provide a phase-advance (*RC*) circuit in the amplifier chain.

The equation of motion of the system and the degree of feedback required from the tacho-generator have been treated by Roosdorp.[16] He shows that, to obtain a system requiring the minimum of changes when the range of the instrument is altered, the amplifier should be divided into two parts having gains a_1

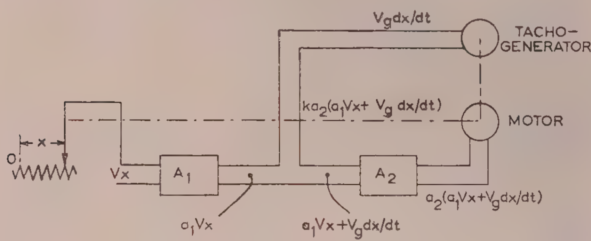


Fig. 11.—Voltages in servo system with damping feedback from tacho-generator.

and a_2 respectively, with the generator feedback coupled in between them, as in Fig. 11.

If x = Displacement of slider from balance point 0,
V = Voltage per unit distance on potentiometer,
k = Force delivered by motor per unit voltage input,
m = Mass of moving system,
V_g = Generator voltage per unit speed,

the equation of motion is

$$m\frac{d^2x}{dt^2} + ka_2\left(Va_1x + V_g\frac{dx}{dt}\right) = 0$$

The solution of this equation is a damped oscillation of x with respect to time, critical damping occurring when

$$V_g^2 = \frac{4mVa_1}{ka_2}$$

In addition, to ensure high sensitivity, the motor must deliver a certain minimum force k_{min} for the smallest value of the displacement x_{min}; hence

$$ka_1a_2Vx_{min} = k_{min}$$

or

$$a_1 = \frac{k_{min}}{ka_2Vx_{min}}$$

On combining this with the previous equation we have

$$V_g^2 = \frac{4mk_{min}}{k^2a_2x_{min}}$$

These last equations show that the value of V_g required is independent of the range and that, on changing the latter (i.e. altering V), it is only necessary to alter a_1, the gain of the first part of the amplifier, in sympathy with V.

Response of a typical instrument with 1 sec traverse time to an instantaneous full-scale change of input is shown in Fig. 12, where the three sections of the curve can be seen: i.e. acceleration to full speed, 0·05 sec; running time, 0·6 sec; decelerating time, 0·3 sec. The response of this instrument to such a step input is given in Table 3, whilst Table 4 shows the frequency of a sine wave which will cause the response indicated.

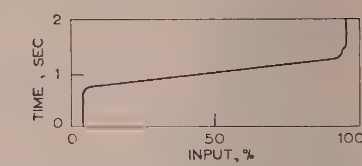


Fig. 12.—Response of servo-operated recorder to full-scale step input signal.

Table 3

RESPONSE OF 1 SEC RECORDER TO STEP INPUT EQUIVALENT Full Scale

Percentage of scale reached (within 0·1%)	10	50	95
Time, sec	0·4	0·6	0·95

Table 4

FREQUENCY WHICH ALLOWS 1 SEC RECORDER TO REACH GIV Scale Values

Percentage of scale peak to peak	10	25	50	95
Frequency, c/s	2·5	1·5	0·9	0·65

(4.3) Mechanical Details

To avoid errors, the pen, scale index and contact carria must move as one unit, the drive between them being kept tau With the linear type of slide-wire all three can be rigidly attach to the contact carriage. A flexible steel tape or cable or a vio string connects the carriage to the output of the motor gear-bo Although, theoretically, backlash in the gear-box should ha no effect on the balance point, yet it could make the moveme jerky near balance, and spring-loaded anti-backlash gears a therefore sometimes fitted, especially in the final drive.

Because so much power is available to drive the system, t pens can be robust and of large capacity to hold sufficient i for several weeks of running; all-glass construction wi syphon action is generally favoured. In some instrumer several pens (up to 6) using different coloured inks may be fitt for multi-point recording, whilst in others dot-printing for 16 24 traces may be arranged.

As with all recorders, most of the mechanism is arranged swing out as one unit for servicing when the front is opene whilst amplifier and vibrator are also arranged for easy acce and removal if necessary.

In addition to the pen recording on the chart, an index mov over a separate linear scale, so that clear, visual indication is al given of the reading.

Most recorders can be fitted with additional devices to conve them into controllers, the simplest being electrical contacts f on-off control. These are beyond the scope of this review b are mentioned as being adjuncts which extend the facilities the recorder.

Most other mechanical details accord with normal record design and so will not be described here.

(5) CONTINUOUS-BALANCE RECORDERS: CAPACITANCE-VARIATION TYPES

To avoid any very small steps there might be in balanci potential when it is derived from a resistive potentiometer, o

anufacturer uses a system with variable capacitance for alancing purposes, and in this way obtains truly continuous ariation.[17] The first models were made in bridge form, with vo resistors and two capacitors, for use with a resistance ermometer, which, of course, formed one arm of the bridge. he general schematic is shown in Fig. 13(*a*), from which it

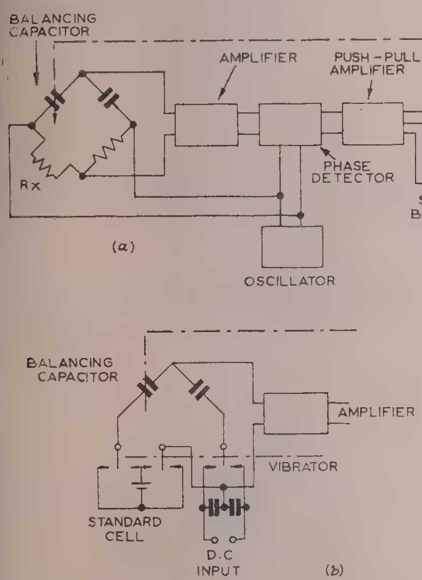


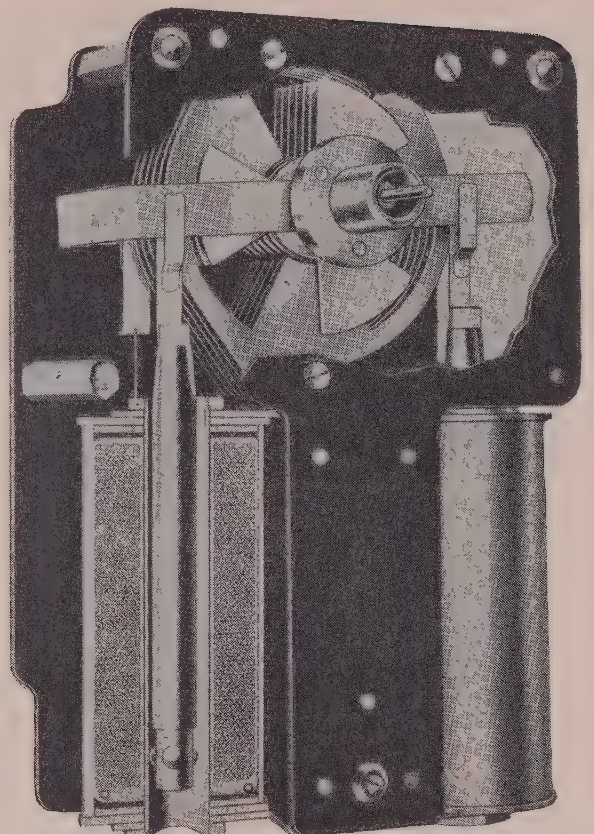
Fig. 13.—Schematics of capacitance-balance circuits.
(*a*) For resistance-change measurement.
(*b*) For d.c. input measurement.

ill be seen that the balancing capacitor in one arm of the bridge operated by opposing solenoids deriving their current from the utput of a push-pull amplifier; these also operate the pen arm move it across the circular record chart.

The variable capacitor is of the multi-vane type with the oving plates arranged as a 3-point star; the construction of this nit can be seen from Fig. 14, which is self-explanatory. The ridge being a capacitance bridge a higher frequency of excita-on than mains frequency is needed, and an electronic oscillator perating at 1 000 c/s feeds both bridge and phase-discriminating ontrol valve in the amplifying chain. The amplifier gain is 10^6 nd the balancing action comes into operation for unbalance oltages of $15\,\mu$V. Full scale span for a step input change akes 3 sec.

An entirely different circuit arrangement is used when dealing vith d.c. inputs, such as the potential developed by a thermo-ouple. Here an all-capacitance bridge is used [Fig. 13(*b*)] vith two of the capacitors being charged directly, one by the nput electromotive force and the other by a standard cell; the urrent drain on this cell being less than $0\cdot1\,\mu$A it is possible to ispense with any auxiliary supply and standardizing means. y means of a 3-pole vibrator the capacitors are periodically onnected together and their charges compared. Any inequality esults in correcting action by the variable capacitor.

Another interesting recorder[20] uses a normal moving-coil d.c. nstrument ($2\frac{1}{2}$ in diameter) as the input element and amplifies ne motion of its pointer through a simple servo system con-rolled by capacitance variation. The meter pointer carries a ght metal vane forming one plate of a capacitor whose other late is carried by the shaft of the recording pen driven by



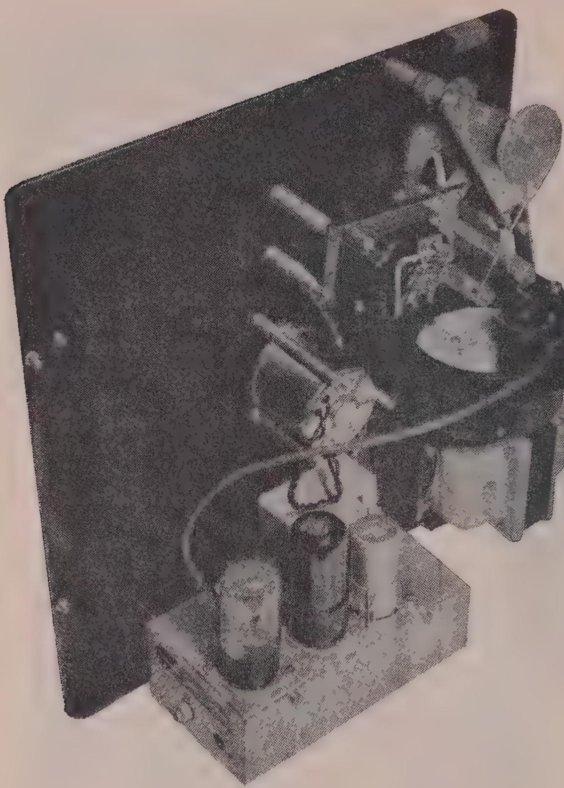
[*Foxboro-Yoxall Ltd.*

Fig. 14.—Capacitor balancing unit for circuits in Fig. 13.
The rotor movement is controlled by the two solenoids.

the servo motor. The servo system follows any movement of the input meter and holds the capacitance between the two plates at a constant value; the separation is about $0\cdot01$ in. A rear view of the complete mechanism is shown in Fig. 15 and the circuit diagram in Fig. 16; it will be seen that the arrangement is simple and this leads to relatively low cost of the instrument.

General accuracy is that of a Grade I indicating meter, i.e. 1% error or better. Standard ranges are 0–50 μA, 0–1 mA d.c. and 0–30 mV d.c. The charts are circular and can be arranged for one revolution in 1, 12 or 24 h. If required, 4-point recording on the chart in different colours can be arranged.

Any deviation of capacitance between meter vane (b) and controller arm (c) (Fig. 16) results in the Hartley oscillator V1 being put into or out of a state of oscillation, depending upon whether the change is a decrease or increase of capacitance. Anode current of V1 (when oscillating) drives the servo motor M in one direction, whilst half-cycle pulses from thyratron V2 will drive it in the opposite direction. The grid potential of V2 is controlled by rectification, between its grid and cathode, of the output from V1, so arranged that when V1 is oscillating the grid of V2 is blocked by the negative charge on C2, whilst cessation of oscillations in V1 allows this charge to leak away and V2 to conduct. At the point of balance, with a certain fixed spacing, the system is hunting back and forth very slightly (about 1/1 000 in at the pointer tip) at 2 c/s; this small oscillation prevents any tendency to pivot-sticking and enhances the accuracy.



[Fielden (Electronics) Ltd.

Fig. 15.—Rear view of capacitance-controlled servo-recorder.

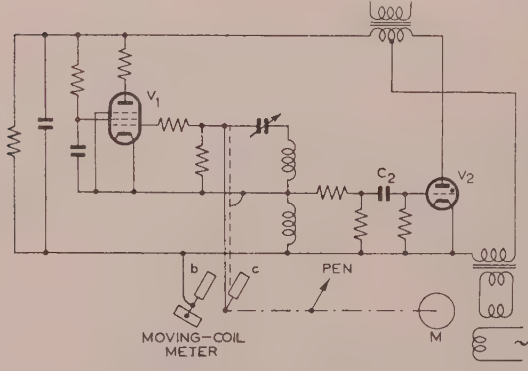


Fig. 16.—Schematic of capacitance-controlled servo-recorder.

(6) CONTINUOUS-BALANCE RECORDERS: ELECTROMAGNETIC-VARIATION TYPES

In an attempt to eliminate all contacts, both in the convertor device and in association with the slide-wire, and to provide stepless variation, a system based almost entirely on electromagnetic devices has been evolved by one manufacturer. D.C. and a.c. bridge arrangements are quite different and will be described separately.

Fig. 17 is a diagram of the arrangement for d.c. input. Heavy negative feedback of current is applied to the convertor-amplifier system, the output current being also fed to the so-called magnetic standard, which has a moving magnet acting as the reference standard; the output from this device is fed (after amplification)

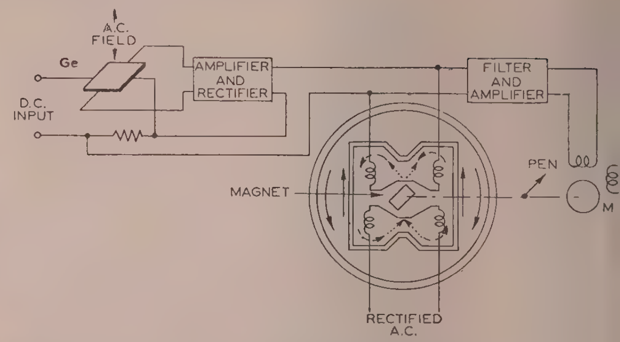


Fig. 17.—Schematic of electro-magnetic balance system for d.c. inpu
The static convertor utilizes the Hall effect.

to a servo motor which drives the recorder pen and moves th magnet until zero output from the 'standard' is obtained an the motor comes to rest. Only in the power stages is the balancin principle employed, and it is not stated why a current derive from the final convertor could not have been used to balanc the input.

The magnetic convertors are of interest. In that for the pow conversion the rotatable permanent magnet is placed betwee two central poles of the thin lamination, around which is place a magnetic shield in which flux linkage also occurs. Each out limb carries two windings. One winding, connected serie aiding, is fed from a 16-volt source with half-wave-rectifie current to produce a flux circulation around the complete co (shown by chain arrows); the other carries the output from th main amplifier (0–5 mA d.c.), the windings being in serie opposition to produce a steady flux upwards in both limbs ar returning via the shield (shown by full arrows). The stead flux produced by the magnet (shown by dotted arrows) is in th opposite direction to that caused by the d.c. windings. At mo positions of the magnet a resultant flux will flow either up down in the limbs, and, since the core is also being excited fro the rectified-a.c. source, an alternating deviation voltage will b induced in the d.c. windings. This is filtered and amplified ar feeds the servo motor, which moves the recording pen and al the permanent magnet until the steady magnetomotive forc are equal in each limb, when no output results and the mot comes to rest.

The static convertor employs the Hall effect in a plate germanium, this plate being located in an alternating magnet field. The d.c. input is applied to one pair of opposite edges the plate, whilst the alternating voltage, which appears acro the other pair, is fed to the succeeding amplifier.

The a.c. bridge for detecting variations of resistance, as in resistance thermometer, has an electromagnetic balancing u driven by the servo motor. This latter turns the rotor to produ a balancing alternating voltage applied to the bridge circu The action will be evident from the diagram in Fig. 18.

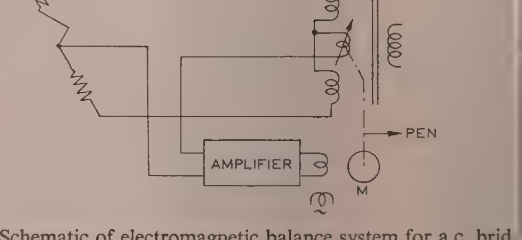


Fig. 18.—Schematic of electromagnetic balance system for a.c. brid

Performance figures for the above instruments are given as llows:

(*a*) *D.C. recorder.* Span 2·5 to 12 mV. Error, 0·25%. Pen speed for full-scale travel, 4, 12 or 24 sec. Sensitivity of the order of 0·03% of full scale, depending on span and pen speed. Chart size, 12 in diameter. Chart speeds, 1 hour to 7 days per revolution.

(*b*) *A.C. bridge.* Performance generally similar, but the instrument is not made for the highest speed, and inputs are quoted only in terms of temperature change (200° F span) and not of resistance.

(7) CONTINUOUS-BALANCE RECORDERS: GALVANOMETER AS SENSING ELEMENT

A few modern instruments still use a galvanometer as the ensing element in association with the potentiometer or bridge, n order to provide a system which does not require a mechanical ibrator for converting direct to alternating current. None of nese uses contacts on the galvanometer or hinders its motion n any way.

One of these is a development of the earlier photo-electrically-alanced potentiometer of Fairchild and Parsegian[9] which was nentioned in Section 2. In the modern version[21] (Fig. 19) the

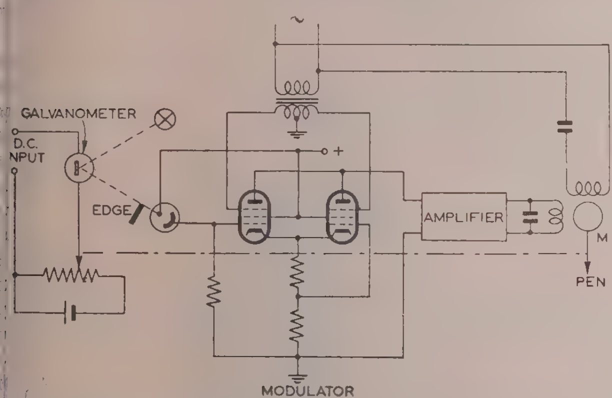


Fig. 19.—Schematic of servo-recorder controlled by galvanometer and photocell.

alvanometer varies the illumination of a photocell which sends . d.c. signal to the paralleled grids of a pair of pentodes arranged s a balanced modulator, the anodes and screen grids being in arallel and supplied with direct voltage whilst the suppressor rids are supplied with alternating voltages of opposite phase. The galvanometer-photocell combination acts as a pre-amplifier nd impedance convertor. The alternating output from the nodulator is amplified and fed to one phase of a 2-phase induction motor in the usual way, this motor driving the slide-wire contact and pen. The 10 in chart is traversed in 1·5 sec, the rror being 0·2% and the sensitivity 0·1% for a scale span of 0 mV or over.

A galvanometer with its pointer carrying a small wire loop which couples with two small fixed coils associated with an scillator has been used for some time in controllers; the system s also employed in a recorder. These coils are in the anode nd grid circuits of a valve oscillator; at the balance point a ertain degree of coupling exists and the anode current of the scillator valve has a standard value. The output is connected lifferentially to the grids of two thyratrons which are then biased qually. A change in one direction of the galvanometer will ause the anode current to increase, and for the other direction t will decrease; thus one or other of the thyratrons will fire. These thyratrons act as relays, their output currents being fed o two electromagnetic clutches which control the drive of the pen carriage and slide-wire contact, the operating motor running continuously.

This recorder uses a straight helix for the potentiometer, 12 in long by ½ in diameter with about 500 turns; the slide-wire contact has 6 contact points, so that effective resolution down to one-sixth of a turn is possible. The result is virtually stepless sensing, at least to 1 part in 3 000; the specification claims 0·1% sensitivity; an error of 0·25%; scale span 8 mV and upwards; and full scale traverse in 30 sec. Automatic standardizing is carried out against a standard cell every ¾ h, the potentiometer being fed from a 1½-volt dry cell.

(8) HIGH-SPEED AUDIO-LEVEL RECORDERS

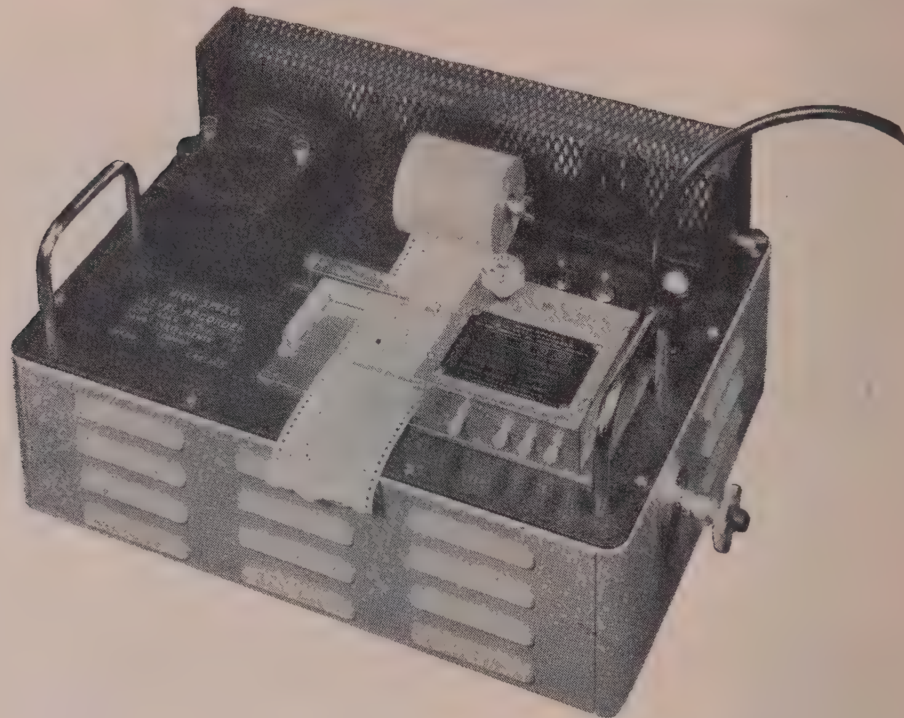
Several versions of audio-level recorders exist. In all of these the amplified output is compared with a reference level (which can be set between 1 and 10 mV) and any deviation is passed to the operating mechanism, which then operates the stylus and at the same time varies the input potentiometer until the output and reference levels are equal. The system differs, therefore, from the continuous-balance potentiometer, since it is the output and not the input which is compared with a reference or balancing level. Hence, in this case, the amplifying and rectifying system must maintain a constant gain.

Instruments of this type were evolved in 1935 by Braunmühl and Weber[8] in Germany and by Wente, Bedell and Swartzel[22,23] in the United States. The former instrument is well known as the Neuman recorder and a model on these lines is now made in this country (Fig. 20). A version with different driving arrangement due to Bruel and Ingard[24] (1949) is made in Denmark. All the instruments are generally similar and employ a paper chart of relatively small width (2–4½ in) of the waxed-paper type, with a sapphire or hardened-steel stylus to score the wax and produce the record. Again, all employ a continuously rotating motor and main drive system with rapid-action clutches to put the pen carriage into motion one way or the other when out-of-balance occurs in the system. The electronic circuit comprises input potentiometer (logarithmic, so that records are given directly in decibels), audio amplifier, rectifier and d.c. amplifier feeding its output (via the reference circuit through two oppositely connected diodes) to two clutch windings, one for each direction of motion.

The Neuman recorder has an ingenious clutch mechanism, shown in Fig. 21. An iron fork, which is connected to the pen arm and potentiometer contact, engages with two iron discs mounted on the motor shaft, on one side or the other according to which clutch coil pulls the fork more strongly; at balance, equal currents flow in both clutch coils. The clutch coils are wound around, but clear of, one of the discs. The United States recorder has the stylus mounted on an endless phosphor-bronze tape driven through the clutches. The Danish method does away with any rotating system (from which linear motion has to be derived to drive the stylus squarely across the chart paper) and uses a form of linear-stroke motor outlined in Fig. 22. An unbalance current from the rectifiers causes a direct current to flow in the coil attached to the stylus arm in one direction or the other. The coil moves longitudinally in a constant radial magnetic field (similar to that of a loudspeaker) and takes up a position where balance occurs; the circuit is arranged so that maximum restoring force is obtained when the coil moves a distance equal to the pitch of the potentiometer winding.

General characteristics for these recorders are as follows:

Scale span, 10 to 75 dB. Error, 0·2–1·5 dB. Response time (full scale), 0·05 or 0·15 sec. Recording speed (maximum), 500–1 000 dB/s. Chart width, 50 mm. Chart speeds, 100 mm/s down to 1 mm/s or less.



[*Dawe Instruments Ltd.*

Fig. 20.—Audio-level recorder using pressure-sensitive waxed paper.

(9) CO-ORDINATE, FUNCTION OR *X–Y* RECORDERS

In plotting the relation of two variables neither of which is time it is sometimes possible to arrange for the recorder itself to provide the input variable to a device being tested. For example, a potentiometer driven by the clock mechanism will provide a variable potential to serve as the *x*-component. Similarly a drum or disc carrying the recording paper may be linked mechanically to the device, giving the effect of angular position as one variable; such a scheme has been used for plotting antenna-radiation diagrams or the frequency response of loudspeakers. Recorders operated in this way have been called by Keinath 'pseudo *x-y* recorders', and since they have only one component which works on the null-balance system, no further description is needed here. In a true *x-y* recorder, co-ordinate plotter or function plotter (all of which terms are in common use), the recording point follows the variations of both magnitudes quite independently, without being tied to a particular motion in the recorder.

With the development of continuous-balance potentiometer recorders as described in Section 4, it has been possible to make electrical recorders of this type plot a function of two variables, such as flux and magnetizing force, stress and strain, or current and voltage. Detailed description is not necessary, since the principles have already been described for a single channel, and in these recorders two similar channels are provided complete with input convertor, amplifier, servo motor and balancing potentiometer. One such channel operates the normal pen system across the chart for the *x*-co-ordinate, whilst the second channel drives the chart, over a limited range, back and forth to follow variations in the *y*-co-ordinate; alternatively the chart may be stationary and the complete pen guide moved back and forth. Thus the curve relating the two variables is plotted directly on the chart.

To achieve rapid response of the chart movement, the torque required is reduced as much as possible by the use of ball-

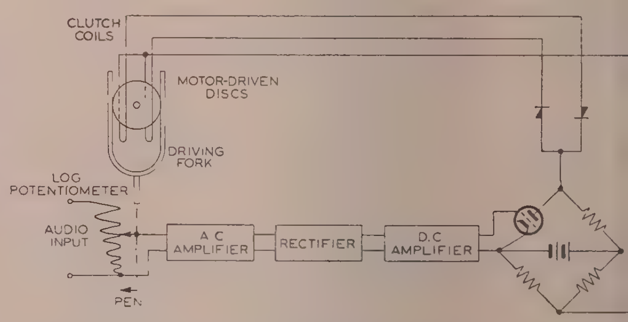


Fig. 21.—Clutch mechanism and general principle of audio-lev recorder.

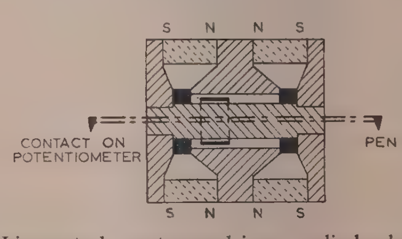


Fig. 22.—Linear-stroke motor used in an audio-level recorder.

bearings, and, as already described, the required amount damping is provided on the motion electrically so that neith oscillation nor undue slowing of the approach to the balan point shall occur. Spring-loaded rollers keep the chart firm located on the driving spigots to prevent the paper slipping o A reference axis is placed above the chart tear-off strip facilitate accurate positioning of the chart in the *y*-directio

Table 5

CHARACTERISTICS OF x-y OR CO-ORDINATE PLOTTERS

	Make of instrument				
	F	G	H	J	K
Scale span x (pen)	0–5 to 0–50 mV	0–2·5 to 0–10 mV	0–18 V or less	0–5 mV to 500 V	0–5 mV to 0–100 V
Scale span y (chart or pen guide) ..	0–5 to 0–50 mV	0–10 mV	0–30 V or less	0–5 mV to 500 V	0–5 mV to 0–100 V
Error, x, %	0·25			0·25	0·25
Error, y, %	0·5		0·2		0·25
Response time, x, sec	4½ (or 12 or 24)	3 (can be 1)	3½–180	0·5	1
Response time, y, sec	4½ (or 12)	4	6–300		1
Chart size, x, in	10	10	18	8½	11
Chart size, y, in	10	10	30	11	16½
y-movement by	Chart	Chart	Pen guide	Pen guide	Pen guide
Type of unit	Panel mounting	Panel mounting	Large plotting table	Table	Table
Special features					A drum type also available with chart 8½ × 11 in

[F. L. Moseley Co. and Frathom Co. Inc.

Fig. 23.—Table-model function plotter.
Chart size 11 in × 16½ in.

an overdrive may be fitted on the winding spools so that the paper is always held taut. The moving system of the chart drive possesses considerably greater inertia than the pen system, and it is usual, therefore, to operate at somewhat lower speeds than can be done in the single recorder. In Table 5 are listed the principal characteristics of several makes of x-y recorder, some of which are small unit instruments (Fig. 23) whilst others are in large table form and used, for example, in conjunction with analogue computers. These tables measure 60 in × 30 in and have traverse times of 2½ and 1¼ sec respectively. Other and special applications are in plotting equipotential lines[25] and electron trajectories[26] in conjunction with electrolytic tank analogues.

Whilst most general applications will be the recording of two input voltages or currents, there are occasions when a synchronous link to the recorder can be used for one variable. Some recorders are designed specifically for such working, e.g. devices for plotting the radiation diagrams of aerials,[27] but instrument F in Table 5 is so designed that it can be changed to operate by this method if desired. This permits direct linkage, by means of a Selsyn system, to a mechanical transducer which is responsive to one variable.

(10) SCANNING OR SWEEP-BALANCE RECORDERS

For increasing the number of input signals which can be recorded on a single instrument in a reasonable time, a higher speed of traverse is required than the normal potentiometer recorder can provide. Keinath[19,28,29] has devised a system in which continual scanning over the full scale of the slide-wire is made, and as the contact moves through the balance point a single point is recorded on the chart; this is a continuous process, so that problems of inertia and hunting are absent.

The basic diagram of one form is shown in Fig. 24; the principle is easy to understand from this. Motor M oscillates the slide-wire contact and recording stylus continuously over the potentiometer; in practice a rotary-type potentiometer is

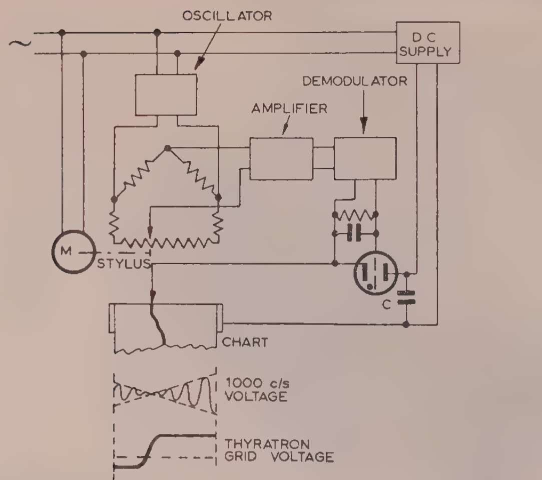


Fig. 24.—Schematic of sweep-balance recorder, stylus scanning.

used. As the contact moves through the point of balance a rapid change of sign or phase in the output from the bridge takes place. After amplification this is caused to trigger a thyratron to pass a pulse of current from the charged capacitor C through the stylus, and this makes a mark on the chart of Teledeltos paper; each sweep thus produces one point on the record. The bridge and demodulator are fed by a 1 000 c/s oscillator.

Keinath emphasizes that this type of recorder would have its greatest application in multi-point recording. In a later paper[30] he elaborates on the idea somewhat and suggests that all existing indicating instruments on a process plant might be superseded by a single sweep-balance recorder to provide both graphical record and indication for all the points, the records being of post-card size.

Several alternative arrangements are possible, but the one most favoured is to arrange the sweep motion in association with the chart movement (the opposite of that shown in Fig. 24); this is because the chart system possesses the greatest inertia and it is preferable, therefore, to keep it in continuous motion. The direction of movement of the chart then represents y whilst x is across the chart, the position of the pen being determined by its own driving mechanism. For an x-y recorder the pen position would be derived from a self-balancing potentiometer circuit, whilst if the plot were to be a function of time the pen could be moved across by the chart-drive motor, through suitable gearing. It will be realized that the sweep action can only be applied to one of the input magnitudes.

If the sweep motor is arranged to drive two potentiometers with their outputs connected to the same stylus (via an isolating double-diode valve) two points will be plotted per revolution, one for each separate input. Alternatively, two separate styli, insulated from each other and spaced half the chart-width apart, will enable separate records of two inputs to be obtained, each on half the paper width. By a combination of the two arrangements and by switching different inputs to the recorder in synchronism with the sweep motion of the chart a large number of traces can be obtained.

These recorders are not in general production but the characteristics of a prototype model are as follows:

Chart width, 10 in. Chart length, 30 in. Chart speed, 4 in/s.
Number of frames in chart length, 12. Number of frames in chart width, 2. Total, 24.
Size of diagrams, 2·2 in high × 5 in wide.
Total number of records, 48. Scanning time, $7\frac{1}{2}$ sec.
Error, 1%.

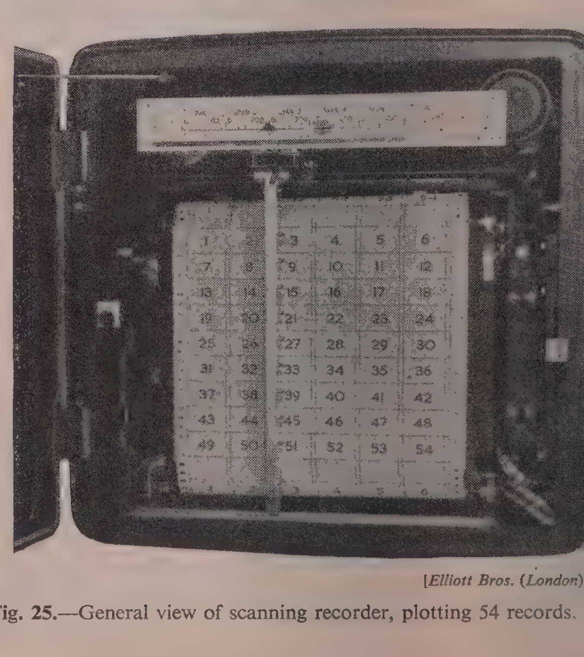
The smaller size of record demands some sacrifice of accura but with 1% error this is still the normal for industrial-ty instruments; the scanning rate is also much higher than can achieved by other methods. In noting the similarity of t system with some facsimile receivers, Keinath considers t much higher speeds should be possible.

In his paper, Keinath[19] suggests also that a helix on a dr above the recording paper and a fixed-bar-type contact on other side would give the effect of a sweeping stylus* as in Fig. Such a system is capable of high speeds and can be applied continuous strip-chart recording. The arrangement has b employed by Carlisle and Spencer,[32] who adopted, for recorder proper, a standard receiver unit of a picture-telegra equipment based on the same scanning system, with a scan t of 1 sec across the chart.

The recording paper is a moist electrolytic one speci developed for facsimile recording and giving a clear black on a white ground. The definition obtainable is good, d 0·025 in in diameter being produced with a one-turn helix a 12 in-wide drum of $2\frac{3}{4}$ in diameter; the marking voltage 40–60 volts. With appropriate switching, up to 12 input poi can be dealt with. The scale span is 0–5 mV and upwards, error in general is 1%, allowing for any shrinkage of the pa on drying (about $\frac{1}{16}$ in).

Another method of scanning to obtain miniature records slowly varying phenomena has been devised by the Uni Kingdom Atomic Energy Authority[37] and uses a modificat of the recorder described in column A of Table 2. One arm the resistance-bridge network is tapped at six points so that separate zero-balance points are obtained, evenly spaced acr the full chart. The normal pen carriage is fitted with a vert bar carrying nine pens. The pens and the tapping points switched sequentially to the resulting 54 input points. T system is a relatively low-speed one and requires from to 8 sec per point, depending on the sequence adopted; e record 'chart' measures about $1\frac{1}{2} \times 1$ in. Fig. 25 is general view of the instrument.

* The helix-and-bar system as a scanning device dates back farther than this an interesting use of it is made in a German high-speed telegraph printer.[31] actually builds up letters or figure characters on a tape in accordance with the re of pulse signals timed from the start of the helix each revolution.



[*Elliott Bros. (London)*]

Fig. 25.—General view of scanning recorder, plotting 54 records.

(11) NORMAL DEFLECTIONAL INSTRUMENTS WITH BALANCING POTENTIOMETER

The self-resetting-potentiometer principle has been applied to moving-coil deflectional-type instrument to provide a quick-sponse recorder. To the pen arm is attached a light contact oving over a small potentiometer (fed from a stabilized d.c. ource), and the system sets itself so that the potential thus picked f is equal to the input potential as fed to an amplifier. The oving coil is centre-tapped and there is no control spring; the en takes up a position where the currents in the two halves of he coil (fed from a differential amplifier) are equal.

With such an arrangement the system can follow sine-wave oltages up to 15 c/s with an amplitude error not exceeding 15% r a peak-to-peak amplitude of 1½ in on the chart. At smaller mplitudes the response is improved and the pen will then follow omewhat higher frequencies. Full-scale span is obtained for 5 volts. Chart speeds can be arranged between ½ and 6 in/s n one model and between 2 and 24 in/min on another. Either k or Teledeltos recording is provided. The instrument is ade as a duplex one with two completely separate channels.

(12) STROBING POTENTIOMETER RECORDER

Records of high-speed recurring waveforms are usually btained by cathode-ray oscillography. A method of plotting irectly by pen on paper has recently been shown in an experi-iental recorder which is, basically, a self-balancing recording otentiometer on the lines already discussed. It cannot follow he variations of potential in the waveform directly, but since he waveform is a recurrent one it is possible to plot a very small ortion at a time by selecting a portion on the waveform, from which an imprint is then obtained on the chart. This point-by-oint plotting is done sequentially, in point of time, throughout he duration of the wave, and this parameter is the x-co-ordinate n the chart.

This is precisely one way in which Callendar[34] used his first otentiometer recorder to plot the waveform of voltage and urrent of the mains supply. He selected the voltage to be ecorded from a particular point of the cycle by means of slowly otating brushes on a potentiometer, the motion of these and the ecord chart being geared together. His plots for one cycle of he a.c. mains occupied 50 min; that was 58 years ago and the wheel has now turned full circle! But with modern techniques sing servo motors, electronic amplifiers and strobe pulsing xactly the same method is possible for much more rapid henomena and plotting may occupy ¼–½ min.

With the above outline and Fig. 26 the principle of the method

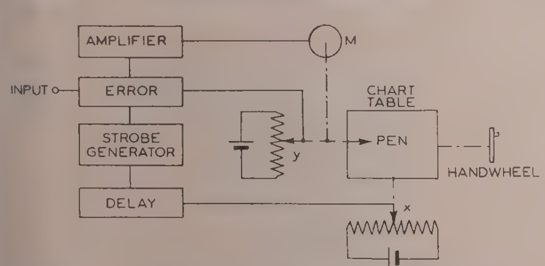
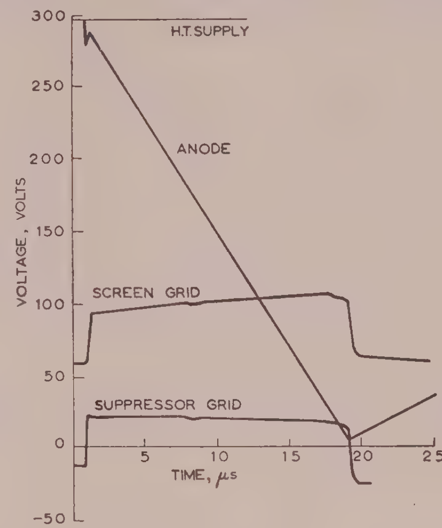


Fig. 26.—Schematic of strobing potentiometer recorder.

hould be clear. As usual, the recording pen, balancing potentio-meter, deviation detector and amplifier follow the normal practice nd record amplitude of the signal. The strobe pulse acts as a ate in the detector and only allows comparison of input and otentiometer potentials to take place at a particular instant on he wave—repetitively, of course, over many cycles. The strobe-pulse position is linked with the x-direction of the chart and so advances along the time scale as the paper is moved past the pen. It is not necessary to provide steady motion for the chart and it may be driven by hand. The pulse is short enough to resolve events down to a few millimicroseconds. A typical record is shown in Fig. 27, on which the scales have been indicated.



[*Ekco Electronics Ltd.*

Fig. 27.—Typical record of Miller integrator waveforms obtained on the instrument of Fig. 26.

(13) ACKNOWLEDGMENTS

Information about their products has been freely given by many manufacturers during the preparation of this review, and thanks are due to the following firms for assistance in this way: Barr and Stroud Ltd., Cambridge Instrument Co., Ltd., Dawe Instruments Ltd., Dobbie McInnes Ltd., Ekco Electronics Ltd., Electroflo Meters Co., Ltd., Elliott Bros. (London) Ltd., Everett, Edgcumbe and Co., Ltd., Evershed and Vignoles Ltd., Fielden (Electronics) Ltd., Foster Instrument Co., Ltd., Foxboro-Yoxall Ltd., Honeywell-Brown Ltd., Integra, Leeds and Northrup Ltd., George Kent Ltd., Philips Electrical Ltd., and Sunvic Controls Ltd.; also to Electro Instruments, Inc., F. L. Moseley Co. and Frathom Co., Inc., and the General Electric Co. in the United States and Bruel and Kjaer in Denmark.

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DISCUSSION ON 'DESIGN OF MICROWAVE FILTERS WITH QUARTER-WAVE COUPLINGS'*

Mr. R. Levy (*communicated*): The authors state that the use of quarter-wave instead of three-quarter-wave couplings reduced the length of a 5-section filter by 9 in. It would be possible to reduce its length by a further 3 in if a direct-coupled filter were used, eliminating the quarter-wave coupling sections entirely.[A, B] In order to make a direct-coupled filter the values of normalized susceptances must be extended to at least 200 and this has been achieved by using more than three stubs. The susceptance is in fact a rapidly increasing function of the number of stubs, and five should be sufficient to obtain a susceptance of about 200 using wires of moderate thickness, e.g. 0·050 in for the 3 cm band. The percentage error in susceptance for a given dimensional tolerance is no greater for a large susceptance than for a smaller one. In the 3 cm band a tolerance of $\pm 0{\cdot}001$ in on the stub positions is sufficient, and this may be obtained by using jigs. In addition to being shorter than its quarter-wave-coupled counterpart, a direct-coupled filter has less dissipative loss since the loaded Q-factors of the cavities are smaller. Whereas in the 5-section filter described by the authors it is necessary to use three stubs of very narrow diameter for the end cavities of small loaded Q-factor, in the direct-coupled filter it is possible to use one or two thicker wires, as the problems of interaction between susceptances does not arise.

Finally it may be mentioned that the use of symmetrical inductive post structures has been previously suggested[C] and reference has been made to their property of cancellation of higher-order modes.[D]

* CRAVEN, G., and LEWIN, L.: Paper No. 2001 R, March, 1956 (103 B, p. 173).

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Messrs. G. Craven and **L. Lewin** (*in reply*): Mr. Levy re mainly to filters employing direct-coupled cavities. Howe both the direct-coupled and quarter-wave-coupled types popular, and so there is a good case for reducing the exces length normally associated with the latter. The direct-coup type will always be shorter, the difference in the example quo being 3 in. However, with conventional three-quarter-w couplings the difference is nearly 12 in.

The useful property of symmetrically placed posts caus higher-order mode cancellation is fairly well known. Howe Simon and Broussand[C] use this arrangement for a differ reason and Gruenberg[D] treats two posts only, without inve gating the best spacing for the cancellation of the third-or mode. Needless to say, not only the symmetrical pair, but the single central post has the property of generating no seco order mode. The triplet has the advantage that, not only the even-order modes cancelled, but also the third and fi when the spacing and radii are correctly chosen.

21.397.7(421)

Paper No. 2069 R
Mar. 1956

THE CRYSTAL PALACE TELEVISION TRANSMITTING STATION

By F. C. McLEAN, C.B.E., B.Sc., Member, A. N. THOMAS and R. A. ROWDEN, B.Sc.(Eng.), Associate Members.

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SUMMARY

The paper gives an account of the factors underlying the siting, lanning and design of the Crystal Palace station. The steps taken attain a high standard of reliability and the considerations that etermined the selection of the Crystal Palace site and the choice of fective radiated power and aerial gain are stated.

The requirements with which the installation had to conform are ven, and the building, plant and equipment are described.

The considerations determining the design of the aerial system are iscussed, and its construction is described. The paper also states the erformance of the aerial system.

(1) INTRODUCTION

The first regular daily television service in the world was arted from the BBC's Alexandra Palace station, London, on e 2nd November, 1936.[1,2] The vision and sound transmitters ad outputs of 17 and 3 kW respectively, and it was many years efore powers higher than these were used for television services ither in this country or abroad. It is noteworthy, too, that the lexandra Palace transmitters have continued in operation irtually unchanged since 1936, and although there have been ery great improvements in the quality of the pictures produced y the modern television camera, the performance of the lexandra Palace vision transmitter has never imposed any ppreciable limitation on the overall performance of the Teleision Service. That this should be so more than 20 years after e station was designed and built is a remarkable tribute to ose responsible for the original installation. However, it is ot surprising that it has now become necessary to replace the lexandra Palace station by a new installation of higher power perating on the same frequencies in Band I (45 Mc/s for vision nd 41·5 Mc/s for sound), sited to cover an area which, with the overage of the other stations that have been built in the meanme, enables the BBC to give nation-wide service. Experience ith the Alexandra Palace station has given the BBC a considerble knowledge of what is necessary for the efficient running of e transmitters of a television service. The specifications for l subsequent stations, including that at the Crystal Palace, ith which this paper deals, were founded upon this experience.

It has been proved that under most conditions a reliable service n be provided with a field strength as low as 0·1 mV/m, and at such a signal is reasonably free from fading. It is, however, bject to interference of one kind or another, and so it was ecided that the new station should be designed to give a field rength of about 0·25 mV/m at the limit of the fading-free zone. he complexity of a television transmitter is such that two transitters should be operated in parallel, or there should be a andby transmitter, if breakdowns are to be kept down to a very w figure; the first alternative has been adopted at Crystal alace.

Taking into account all these points, it was decided that the basic requirements for the new station were

(*a*) It had to be of appreciably higher power than Alexandra Palace.

(*b*) It had to be designed for the highest possible reliability of service.

(*c*) It had to be located on the south side of the Thames.

(2) DESIGN CONSIDERATIONS

(2.1) Reliability

Experience at Alexandra Palace and subsequent television stations has shown that the complexity of a modern installation makes it virtually impossible to rectify any but the most simple faults without an appreciable interruption to the service. At the regional stations this difficulty has to some extent been met by installing standby transmitters of one-tenth the power of the main transmitters. However, this arrangement has the threefold disadvantage that the reduction in power output on changing to the reserve transmitters is greater than is really desirable, that two completely different types of transmitter must be installed, and that there is inevitably some interruption to the transmission in making the change-over. Furthermore, it leaves out of account the aerial and feeder system, and experience has shown that these are two of the most vulnerable elements in the transmitting chain. It is not so much that they give more trouble than any of the other elements, but rather that when a fault does develop there, it is often extremely difficult to clear, because of the adverse conditions under which the work must be carried out.

With these considerations in mind it was decided that the best way of minimizing interruptions to the service due to breakdowns would be to equip the station with duplicate vision and sound transmitters, and to construct the aerial and feeder system in two separate halves, each of which would under normal operating conditions be connected to one pair of vision and sound transmitters. Thus there would be two completely separate chains of transmitting equipment. In the event of a fault occurring anywhere in one chain the power delivered to the aerial system would be reduced by 3 dB, and at the same time there would also be a reduction of 3 dB in the power gain of the aerial (since one half would not be radiating), so that the radiated power would be reduced by 6 dB altogether. There would, however, be no interruption to the transmission.

It was further decided that additional switching facilities should be provided, so that if a fault were likely to persist for a considerable time the complete system could be reswitched at the first suitable opportunity to permit either pair of vision and sound transmitters to feed into both halves of the aerial system, or both pairs to feed into one half of the aerial system. For prolonged breakdowns, therefore, the reduction in radiated power would be only 3 dB, as compared with 10 dB at the regional stations.

Before these conditions were finally accepted, tests were carried out on a number of representative receivers in order to verify

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that a reduction in signal strength of 6 dB for a period of up to half an hour would be acceptable to viewers, and that a reduction of 3 dB for a more prolonged period would also be acceptable. The tests showed that the average receiver could accept a diminution of signal strength of the order of 10 dB before it became impossible to compensate for the loss by adjusting the front-panel controls. It was therefore judged that reductions of 6 and 3 dB would be quite tolerable, and the design of the station accordingly proceeded on this basis.

(2.2) Effective Radiated Power

Experience at the regional television stations had shown that in Band I a signal reasonably free from fading was obtained at distances up to 50 miles from the transmitting station with an effective radiated power (e.r.p.) of 100 kW from an aerial effectively at least 1 000 ft above the surrounding country. It was thought, however, that it would be desirable to improve the signal/noise ratio by some 6–10 dB at this range, and hence that the e.r.p. should be between 400 and 1 000 kW.

As the power is raised, however, every increase becomes progressively more expensive and more difficult to achieve. With this in mind, and after full consideration of the transmitting equipment obtainable, the stresses to which the feeder and aerial system would be subjected and the initial and operating costs, it was finally decided that the installation should be planned on the basis of an effective radiated power of 500 kW. Such a power could, it was estimated, be used without any risk of interference to the service from the co-channel station at Divis in Northern Ireland. Application was accordingly made for this power at the European Broadcasting Conference held in Stockholm in 1952, and the allocation to the London station—and the other high-power stations in the United Kingdom—was for this power.

It was felt, however, that it would not be justifiable to go to this power until the need for it had been definitely proved, but that it would nevertheless be prudent to have a potential reserve in hand against a possible future demand by viewers for a stronger signal, as they became more critical, and also because more Continental stations would eventually be operating in Band I. It was therefore decided that the station should open with an e.r.p. of about 200 kW, but that the power plant and the building should be planned with an ultimate e.r.p. of 500 kW in mind, and that the feeders and feeder switching installations, which are difficult to modify once a station has gone into service, should be built initially for an e.r.p. of 500 kW.

(2.3) Transmission Characteristic

The Alexandra Palace station operates with full double-sideband transmission. When the expansion of the television service outside the London area was put in hand, however, it was realized that there was insufficient spectrum space to allow this system to be used elsewhere, and so vestigial-sideband transmission has been adopted at all subsequent stations. As a result, all receivers designed since about 1950 have been built for vestigial-sideband working, and hence most of the receivers in the London area neither need the information contained in the upper sideband nor take advantage of it. After consultation with the Post Office and industry it was therefore decided that the Crystal Palace station should conform with the other stations and radiate a vestigial-sideband signal. The following advantages accrue from this decision:

(*a*) Spectrum space is saved, approximately 2 Mc/s being left clear for possible other uses.

(*b*) The frequency range over which the transmitting aerial and feeder system must have a good characteristic is reduced; this permits an overall improvement in performance, and may also make it easier to meet the stringent requirements for colour-television transmission.

(*c*) The pass-band of the transmitter circuits is reduced, there enabling their efficiency to be increased, which in turn leads t reduction in operating costs.

(2.4) Economic Considerations: Choice of Aerial Gain

Considerable thought was given to the economic design of t complete system, and in particular to the maximum practical aerial gain. For a station of this size it was desirable to hav much higher aerial gain than had been provided at the region television stations, since this leads to a very considerable redu tion in operating cost by virtue of the reduction in transmit power required.

Against this must be set a number of disadvantages. Fir every increase in gain increases the weight and wind-loading the aerial structure, which requires that the strength of t supporting tower should be increased: this, in turn, adds co siderably to the cost of the tower. Moreover, the cross-secti of the structure on which the aerial is mounted will have to increased to provide sufficient strength, and this results in a mo complex aerial design if a reasonably uniform horizontal rad tion pattern is to be obtained. The distribution feeder syste also becomes progressively more complex and costly with eve increase in gain. Furthermore, as the gain is raised, the vertic radiation pattern becomes increasingly sharp, and it may becom necessary to impose stricter requirements for tower rigidity, order to limit the movement of the aerial under varying wi loading and hence avoid fluctuations in received signal streng This again adds materially to the cost of the tower.

Another important consideration is that as the aerial gain raised, the number of minima in the vertical radiation patte increases. The effect of this is to produce an increasing numb of contours of low field strength near the station, where t received signal will be relatively weak, and—what is mo important—distorted, as a result of the minima being sharp selective with frequency. If reception close in is to be sat factory, steps may have to be taken to fill in these minim particularly at a station such as the Crystal Palace, which is sit in a densely populated area. This makes for greater complex in the aerial and feeder design and also entails a reduction in t effective gain of the aerial system.

It must also be borne in mind that for every 3 dB increase gain the aperture of the aerial must be doubled, so that if t centre of the aerial is to be maintained at a fixed height abo ground, the overall height of the tower—and hence its cost also increase very rapidly with increasing gain. Conversely, if t overall height of the tower is fixed, the height of the centre of t aerial above ground decreases very rapidly with increasing ga

For the Crystal Palace site the Ministry of Transport and Ci Aviation had imposed a limit of 1 050 ft for the height of the t of the structure above sea level. This meant that any increa in the aerial aperture must be compensated by a decrease in t height of the centre of the aerial. Moreover, space had to left for two Band III aerials or one Band III aerial and o Band IV or Band V aerial.

After all these factors had been taken into account and t performance and cost of the various possibilities had been co sidered and compared, it was finally decided that for Band an 8-tier aerial represented the best compromise. It was clea desirable that these eight tiers should be as high as possible the tower without prejudicing the performance of the t Band III aerials or the Band III and Band IV or V aerials whi might be required in the future. In attempting to reconcile the requirements, consideration was given to the possibility of inte leaving one of the Band III aerials on the same structure with t Band I aerial. An investigation of this proposal showed, ho ever, that it would be extremely difficult to achieve an acceptal

uniform horizontal radiation pattern for the two aerials, and that, while the problem was perhaps not insuperable, it was certainly out of the question to design such an aerial system within the time available. The structure had therefore to accommodate the Band III and Band IV or Band V aerials above the Band I aerial.

In the early stages of the design of the tower it had been decided that it should consist of a support tower of tapered form extending 340 ft above the ground, and that the remainder of the structure above this should be of square cross-section with parallel sides, having a width appropriate to the load to be carried and the dimensions of the aerial that each part would support. The original intention was that all the aerials should be mounted on this parallel-sided section, in order to give them the maximum possible elevation. During examination of the problem, however, it was found that it would be possible to erect the Band I aerial partly on the tapered support tower and partly on the parallel-sided section above; the space available for the additional aerials would then be increased by approximately 50 ft. With this arrangement, it would be possible to erect an 8-tier Band I aerial having its centre at 430 ft above ground level, and at the same time leave sufficient space above this either for two Band III aerials, each of which could consist of 16 tiers, or one Band III aerial of 16 tiers and a Band IV or Band V aerial of perhaps 32 tiers.

After careful consideration it was concluded that the depreciation in performance of the Band I aerial due to its being divided between the tapering support tower and the parallel-sided structure above would be comparatively small, and that even after taking this depreciation into account, the service expectations could all be realized. It was therefore decided to adopt this form of aerial, thus leaving as much space as possible on the tower for future aerial requirements. Fig. 1 shows an outline of the tower and the space allocated to the various aerials.

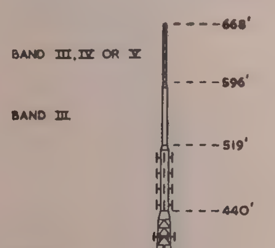

Fig. 1.—Outline of the tower.

(2.5) Choice of Site

When the original television service for the London area was planned in 1935, possible transmitter sites at Alexandra Palace, Crystal Palace, and in the Shooters Hill, Hampstead and Highgate areas were considered.[1] At the time there was little knowledge of the minimum field strength necessary for the successful reception of television in the v.h.f. band or of the propagation of waves at 45 Mc/s over undulating ground, and it was thought that the effective range of the service would be about 30 miles. On this basis the Alexandra Palace site was chosen because its location some six miles north of Central London placed it rather nearer the centre of the densely populated regions of Greater London and the Home Counties than either the Shooters Hill or the Crystal Palace site, and because part of Alexandra Palace was available and suitable for immediate development as a combined transmitter and studio building.

Experience with the service from Alexandra Palace during 1936–39 showed that the effective service range was considerably greater than had been expected, and that under reasonably interference-free conditions an acceptable quality of reception was possible with field strengths down to about 0·1 mV/m. It showed, too, that the degree of fading at distances corresponding to this field strength was generally within acceptable limits. Much more information about the propagation of very high frequencies also became available during the years after 1935. Hence, when the question of a replacement for the original station first came under consideration in 1950 it was apparent that, given a suitable site and with the much greater e.r.p. that had become practicable, it would be possible to extend the service over Kent, Surrey and Sussex without seriously weakening the service to the north and north-east, and to join up fairly well, without excessive overlap, with the service areas of the adjacent stations at Sutton Coldfield and Rowridge.

It became clear that the original site at Alexandra Palace was too far north of the centre of the area to meet the case, and so a suitable site south of the Thames, having both sufficient altitude and favourable ground profiles outwards in most directions, was sought. It was also necessary that the site should have a minimum area of about two acres and that it should be acceptable to the Post Office, the planning authorities and the Ministry of Transport and Civil Aviation.

As a preliminary to a detailed investigation by means of site tests, a theoretical study of the probable coverage from the following sites was undertaken:

The existing v.h.f. transmitting station at Wrotham.
Crystal Palace.
The Shooters Hill district.
Worms Heath, near Warlingham.
Reigate Hill.
A site (at low level) in the Borough of Southwark.

The theoretical study narrowed down the choice initially to Shooters Hill, Crystal Palace and the Southwark site. The sites at Wrotham, Worms Heath and Reigate Hill were not further investigated, because although the coverage over the southern counties would have been much improved, the service in North London would have been relatively too weak compared with the original service from Alexandra Palace. The Reigate Hill site would also have entailed a wasteful overlap with the service area of Rowridge without any compensatory advantage.

Tentative coverage maps showing the calculated positions of the contours of the median field strengths of 5, 0·5 and 0·1 mV/m for an e.r.p. of 400 kW and a mast height of 750 ft were then prepared for the three sites, and from these maps the population that would receive a service of these three grades was estimated. The results are shown in Table 1, which also gives the corresponding figures for the original service from Alexandra Palace.

The Table shows that, by moving from Alexandra Palace to either Crystal Palace or Shooters Hill and taking advantage of the great increase in e.r.p. that had become practicable, some 2 500 000 more people would be brought within the acceptable service area (0·1 mV/m), and that the number of people getting

Table 1

Site	Population within contours of given median field strength		
	5 mV/m	0·5 mV/m	0·1 mV/m
	$\times 10^6$	$\times 10^6$	$\times 10^6$
Shooters Hill	10·1	12·1	15·0
Crystal Palace	10·0	12·0	15·2
Southwark	10·0	12·2	14·1
Alexandra Palace (original service)	7·2	10·6	12·5

a relatively good grade of service (not less than 0·5 mV/m) would be increased by about 1 500 000. Moreover, the calculations showed that no one who was getting an acceptable service from Alexandra Palace should receive an unacceptable service from either the Crystal Palace or Shooters Hill sites. This was a most attractive prospect, which, if verified by the field trials, would fully justify the change of site. The Southwark site, although likely to provide a good service of the higher grade to a large population by virtue of its central position, was not so good far as the outer areas were concerned, and hence did not fu one of the most important requirements.

On this basis it was decided to verify the theoretical studies carrying out site tests from Crystal Palace, and subsequently fr Shooters Hill should the results for Crystal Palace prove c appointing. Accordingly, in January, 1952, a mobile site-test transmitter was set up at Crystal Palace with an aerial that co be raised some 600 ft above the ground by means of a balloo Throughout the next four months an exhaustive field-stren survey of the whole area within a 70-mile radius from the tra mitter was made by two measuring teams using vehicles equipp to measure and record the field strength continuously as th moved along. Every locality was explored in detail, and co tinuous recordings of the field strength over a total distance 3 500 miles were obtained.

The field-strength contour map (Fig. 2) is based on the resu of this exhaustive survey. The map shows the expected positio of the 5, 0·5 and 0·1 mV/m contours for an e.r.p. of 200 k and an 8-tier aerial with its centre 430 ft above ground, toget with the corresponding contours for the original service fr

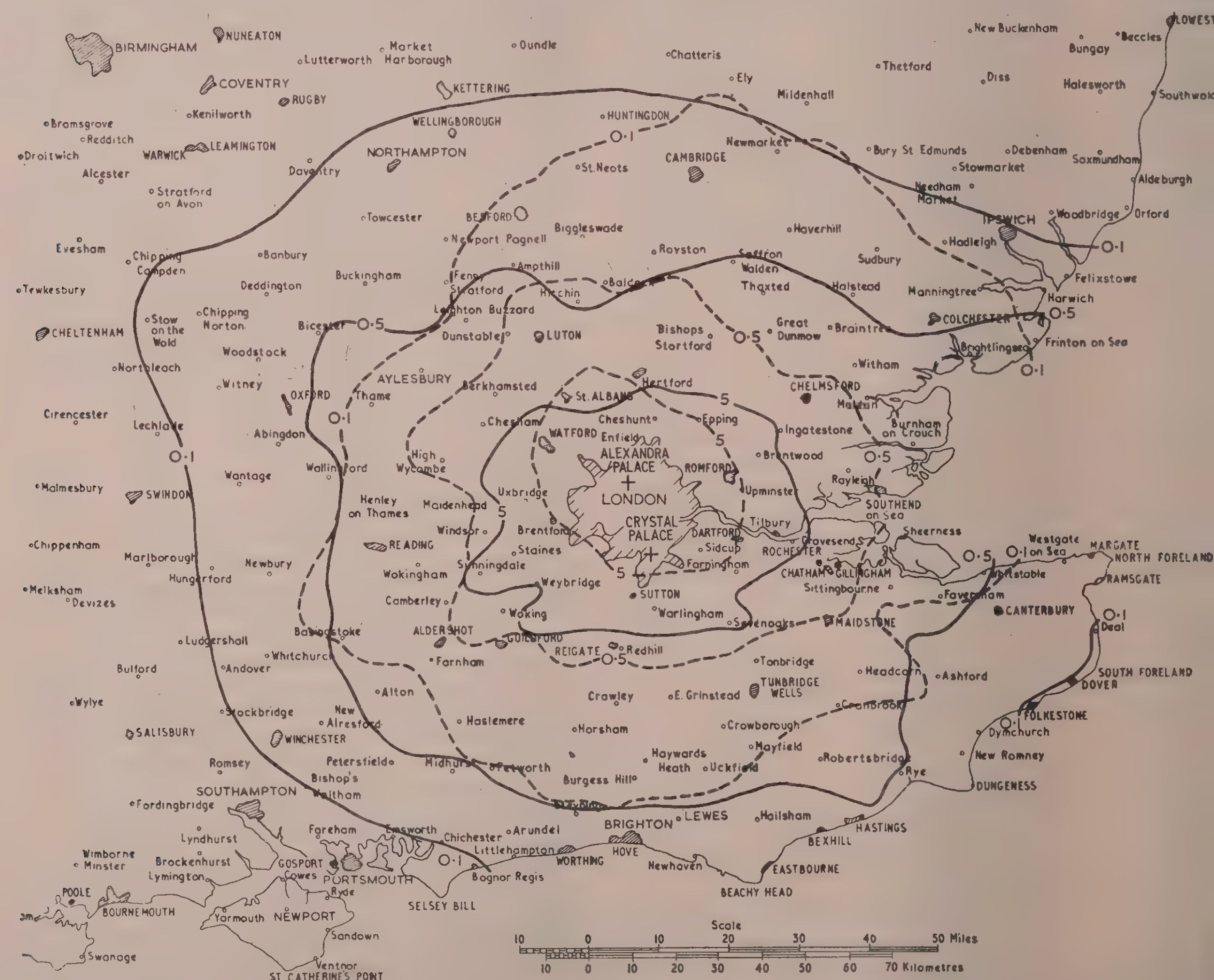

Fig. 2.—Field-strength contours for the Crystal Palace and Alexandra Palace stations.

——— Crystal Palace (200 kW e.r.p.; centre of aerial 430 ft above ground).
------- Alexandra Palace.

Alexandra Palace. It will be seen that the first requirements for a new site, namely that the outer coverage should be much improved, particularly in Kent, Surrey and Sussex, is adequately fulfilled by the Crystal Palace site. Only the area immediately surrounding Alexandra Palace and some districts to the north of London experience a decrease in field strength, and although these areas still receive an adequate service, a minority of viewers may need better receiving aerials. The coverage improvement is clearly demonstrable: within the measured 5, 0·5 and 0·1 mV/m contours Crystal Palace will serve 9·2, 12·1 and 14·5 millions respectively, compared with 7·2, 10·6 and 12·5 millions served by Alexandra Palace.

The experimental results fully confirmed the original theoretical expectations, and it was therefore decided not to make site tests from Shooters Hill, more especially as this site was not expected to offer any substantial advantage over Crystal Palace.

No detailed theoretical or experimental study was made of the relative merits of the various sites for possible future transmissions in Bands III, IV or V. As regards Band III (174–216 Mc/s), experience suggested that if a site were fully satisfactory for Band I transmissions it would, to a first order, also be satisfactory for Band III, since it was known that the median field strength for a given e.r.p. and aerial height was normally of the same order on both bands out to a minimum distance of some 60 miles over average terrain. The only known requirement for good u.h.f. (Bands IV and V) coverage is that the transmitting aerial should have the maximum possible population within its quasi-optical range. This requirement would be fulfilled at the Crystal Palace site, located as it is near the centre of the London basin.

(3) TECHNICAL AND OTHER REQUIREMENTS

(3.1) Transmitter Installation

The installation was planned and the equipment specified to conform with the following requirements:

(*a*) The transmitting equipment to be completely duplicated and to comprise two vision transmitters each capable of a peak-white output power of 15 kW, the two sound transmitters each capable of an unmodulated carrier output power of 4 kW. The transmitters were required to meet a rigorous performance specification when operating singly or in parallel. In addition, it was known from the offer by the manufacturer that the vision transmitters would be designed with the requirements for the transmission of a colour signal of the N.T.S.C. type in mind, in respect of the performance of the transmitter modulation frequencies in the neighbourhood of a possible colour sub-carrier frequency. This does not imply that an N.T.S.C. system, or indeed any colour system, will be used. A colour system that transmits the colour information outside the channel would, of course, impose much more stringent requirements for transmitter performance. The transmitters are described in a companion paper.[4]

(*b*) The layout of the station to allow for the subsequent addition of amplifiers so as to raise the power output of each of the vision and sound transmitters to approximately 50 and 12 kW respectively. Provision also to be made for extending the station in the future in order to enable further transmitters to be installed.

(*c*) Power-supply equipment of sufficient capacity to handle the load imposed by two 50 kW vision transmitters and two 12 kW sound transmitters to be installed at the outset, with provision for additional transmitters of comparable power for a second programme.

(*d*) The feeders and feeder switchgear to be designed to handle a power of 100 kW into each half of the aerial.

(3.2) Radio-Link Reception

It was appreciated that the Crystal Palace tower, being the highest structure in London, would offer unrivalled facilities as a radio-link reception point for outside broadcasts. It was therefore specified that the tower design should include provision for mounting eight s.h.f. receiving aerials for this purpose.

(3.3) Economy of Operation: Staff Costs

In the operation of a television transmitting station the cost of the staff represents a major part of the total running costs; hence, economic use of staff is essential if the total running costs are to be kept down. At the Crystal Palace station the decision to install duplicate chains of transmitting equipment, which was taken primarily in the interests of reliability, had the important secondary advantage that the station could be run without the reserve of man-power that would be necessary if immediate attention to faults was required. This fact, together with the layout adopted for the equipment, has made it possible to run the station with only three men on watch at a time.

(4) BUILDING, PLANT AND EQUIPMENT

(4.1) Site and Building

Negotiations for a site within the Crystal Palace grounds were opened with the L.C.C. towards the end of 1951. After considering various areas, the L.C.C. offered a 2-acre site to the north-east of the upper terrace on condition that the building was buried below the terrace, so that the public could have access to the whole area in accordance with the proposed redevelopment plans for the Crystal Palace grounds. This made the construction of the building more costly and also meant that mechanical ventilation had to be provided throughout the greater part of it.

The layout of the building is shown in Fig. 3. The structure is of reinforced concrete, with brick partition walls. The offices, mess room and common room are on the front side overlooking the lower terrace, where they have the advantages of natural lighting and ventilation. The remainder of the building, including the transmitter hall and other technical areas, depends on artificial lighting and mechanical ventilation. The technical equipment is all on one floor, except for the ventilating plant, which is on an upper floor. The arrangement of the building and the tower has been so planned that the building can be extended after further excavation, without endangering the tower or causing any interruption to the service on Band I, in order to accommodate additional transmitters for possible future transmissions in Bands IV or V or for other purposes such as colour television.

(4.2) Power Supply

Duplicate mains power supplies at 11 kV are installed, each supply having a capacity of 500 kVA. The two supply cables originate from independent networks, and hence there is virtually a guaranteed power supply, although in the unlikely event of their both failing the station would be shut down. A 20 kW Diesel-driven alternator with automatic starting has been installed to maintain the obstruction lights on the tower and provide emergency lighting in the building. This alternator also maintains the supply to the s.h.f. radio-link receiving equipment, thus ensuring that any programme being taken over the link equipment and being broadcast by other stations will not be interrupted by a local supply failure.

Distribution within the building is at 415 volts, 3-phase, with separate feeders to each of the vision and sound transmitters. The supply to the electronic equipment other than the transmitters is taken through an automatic voltage regulator which limits the voltage variation to within $\pm 1\%$ of the nominal value for a change of supply voltage of $+5$ to -15%.

Provision has been made for the addition of further power plant to bring the total installed capacity up to 1 500 kVA, in order to cater for additional transmitters for a second programme.

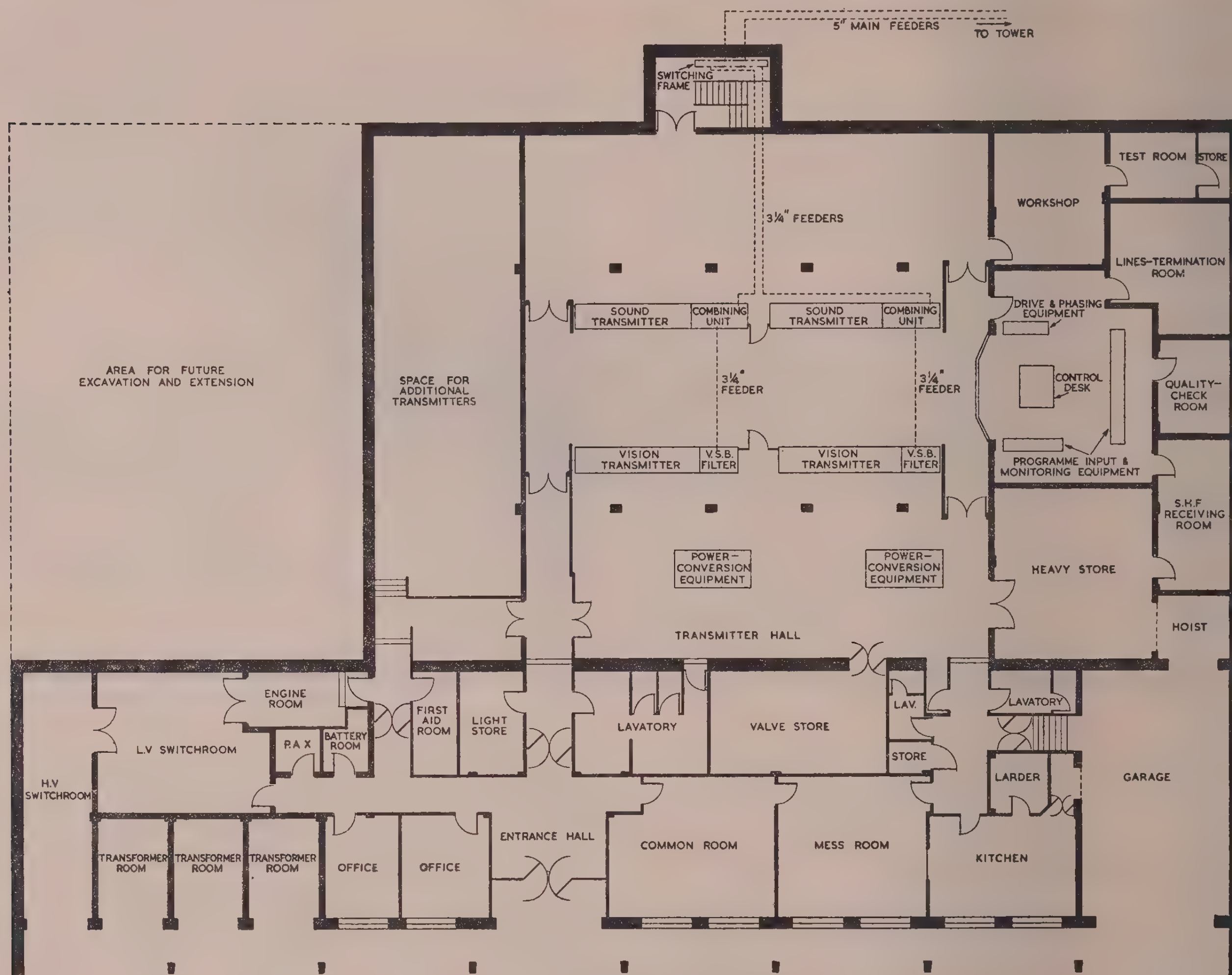

Fig. 3.—Layout of the transmitter building.

(4.3) Programme Input Equipment

Duplicate 1 in-diameter coaxial tubes are rented from the Post Office for the vision-programme feed to the station. Normally one tube carries the programme from the switching centre at Broadcasting House and the other is held in reserve, but both are reversible and the reserve is used as necessary for feeding programme received over the s.h.f. radio-link equipment to Broadcasting House. The tubes terminate in equipment[5] of BBC design, which has several novel features, and provision has been made for additional terminal equipment which will enable each tube to carry more than one programme simultaneously.

(4.4) Layout of Transmitter Equipment

The layout of the transmitters is shown in Fig. 3. Space has been left for additional amplifiers to be installed in the future, if required, in order to increase the vision and sound transmitter powers to approximately 50 kW and 12 kW respectively. The combining units for the outputs of the vision and sound transmitters are mounted in cabinets similar in appearance to the transmitters and located in line with the sound transmitters—an arrangement which results in a convenient feeder layout. The switching framework carrying the feeder switches, diplexer and transformer, which enable the various transmitter-aerial co binations to be set up, are located along the run of the tw $3\frac{1}{4}$ in-diameter coaxial feeders from the transmitter combini units at the point where the 5 in-diameter feeders leave the buil ing on the way to the tower. The air blowers and filters for t transmitters are in a first-floor room above the office bloc together with water tanks and pumps for the cooling of t various test loads. Space is also available in this room for t duplicate distilled-water circulating and cooling plants whi would be required if the additional power amplifiers we installed.

The control room has a window facing down the transmitt hall, with the control desk for the vision and sound transmitte located so that all the transmitters are visible from it. The roo is acoustically treated to facilitate sound monitoring, and it hous the duplicate drive and phasing equipment for the transmitter the vision- and sound-programme input equipment and a tran parency scanner for originating test and caption cards locall Normally, only one man is on watch in the control room.

Behind the control room are the quality-checking room, whic is acoustically treated for critical sound monitoring, and t s.h.f. receiving room.

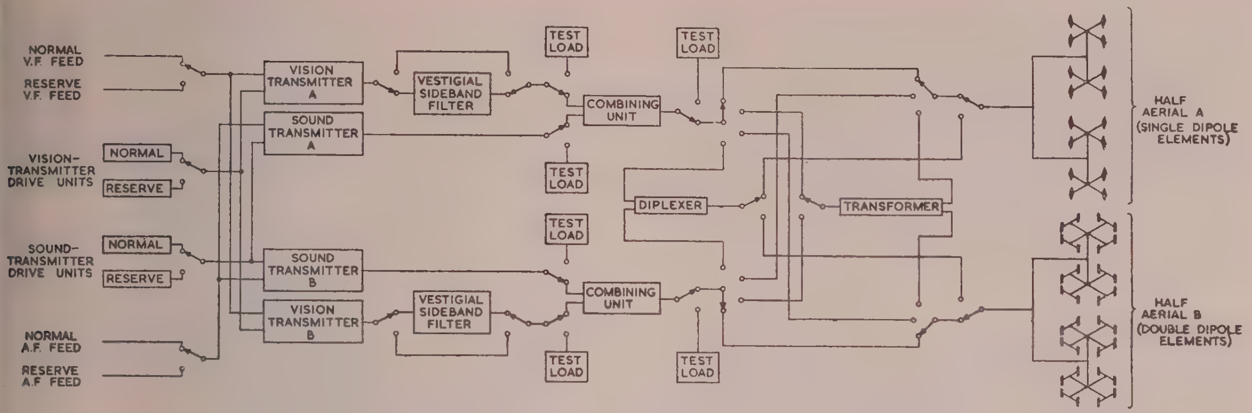

Fig. 4.—Schematic of duplicate chains of transmitting equipment.

(4.5) Transmitter and Aerial Switching

The arrangement of the duplicate chains of transmitting equipment is shown in Fig. 4. Particular care has been taken to avoid common links in the two chains, which might result in a single component failure putting them both out of action; for example, the normal and reserve vision and sound programme feeds to the transmitters are taken through separate isolating amplifiers, which obtain their supplies from different power units and are therefore quite independent of one another. At certain points, however, a common link is unavoidable, and where this occurs the equipment is duplicated. For instance, the r.f. drive for both chains inevitably comes from a single source, but spare drives are maintained in readiness for an immediate change-over in the event of a breakdown.

Each transmitter and combining unit is provided with a test load, so that the location and rectification of a fault in this section can proceed while the station continues in operation. If a fault develops in one of the vestigial-sideband filters, the filter can be by-passed to restore the radiated power to its full value. Very few receivers would be adversely affected by the abnormal amount of energy in the upper sideband under these conditions, and no serious interference with other services would result.

Under normal conditions both chains are in operation, with one pair of vision and sound transmitters connected to one half of the aerial, and the other pair to the other half, i.e. pair A to half-aerial A, and pair B to half-aerial B. In an emergency, any of the following transmitter-aerial combinations can be set up by means of eight coaxial feeder switches interposed between the inputs to the main feeders and the outputs of the test load switches associated with the combining units:

(*a*) Both pairs of vision and sound transmitters to either half of the aerial via the diplexer.
(*b*) Either pair of vision and sound transmitters to both halves of the aerial via the transformer.
(*c*) Pair A of vision and sound transmitters to half-aerial B, and pair B to half-aerial A. This cross-over facility was included because the switch positions were available and it could be provided at small additional cost.

(4.6) Test Equipment

Test equipment is provided for routine performance measurements on the vision circuits to Broadcasting House and on the vision and sound transmitters. The performance of the feeder system can be checked by means of power and reflection-factor meters.

(4.7) Radio-Link Receiving Equipment

Eight parabloid aerials for receiving radio-link transmissions in the band 4 400–4 800 Mc/s from outside-broadcast locations are mounted on platforms projecting from the tower 430 ft above ground. Each aerial gives a gain of 33 dB and can be set on any desired bearing within an arc of 180°, with an absolute accuracy better than $\pm 1°$, by means of a remote-control system operated from the transmitter building. The output from the aerials is taken via a waveguide and flexible coaxial connection to receiving equipment within the tower structure and thence, at intermediate frequency, to the s.h.f. receiver room. The receiving equipment on the tower is provided with remote tuning facilities and automatic frequency control.

(5) FEEDER SYSTEM

(5.1) Main Feeders

The decision to have a transmitter and aerial system comprising two separate chains meant that two main feeders, each with an associated distribution feeder system, must be provided. In order to carry the maximum power ever likely to be employed and also to minimize losses, it was decided to use 5 in-diameter coaxial copper air-spaced feeders of 51·5 ohms characteristic impedance. The specified performance for these feeders was briefly as follows:

(*a*) Each feeder to be capable of carrying simultaneously a vision power of 100 kW peak-white carrier on 45 Mc/s, amplitude modulated by the standard BBC television waveform, and a sound carrier power of 25 kW on 41·5 Mc/s, 100% amplitude-modulated. The loss in each feeder not to exceed 0·075 dB per 100 ft at 15° C and 0·09 dB per 100 ft at 50° C.
(*b*) With the feeders terminated in an optimum impedance, the measured input impedance to be within a 0·97 circle on the Smith Chart[6] between 41·5 and 48 Mc/s. This performance specification ensured that any delayed images resulting from discontinuities in the feeders would be well below the level of visibility. It also ensured that the performance of the main feeder system would be satisfactory for the transmission of colour-television signals with the chrominance carrier above or below the luminance carrier.

(5.2) Distribution Feeders

It was decided that no attempt should be made to compensate in the distribution feeder system for any shortcomings in aerial bandwidth. This decision enabled the full-scale design of the aerial and distribution feeder systems to proceed in parallel and independently, with a consequent saving of time, although it imposed a more stringent requirement on the design of the aerial elements. The appreciable difference in cross-section of the structures supporting the upper and lower halves of the aerial made it impossible to use physically similar distribution feeder systems, and two systems of different design, but with the same electrical performance, were evolved, this performance being as

nearly as possible immaculate from the bandwidth aspect. The design was based on the following outline specification:

(a) Each half of the distribution feeder system to be capable of carrying the same power as its associated main feeder.

(b) With each of the branch feeders leading to the aerial elements terminated in its optimum impedance, the input impedance of each independent half of the distribution feeder system to lie within a 0·98 circle on the Smith chart[6] between 41·5 and 48 Mc/s. This stipulation ensured that the degradation of aerial bandwidth due to the distribution feeder system would be insignificant. As with the main feeders, it also ensured that the performance would be satisfactory for the transmission of colour-television signals without readjustment.

In order to obtain the maximum possible bandwidth, both distribution feeder systems were designed in full branch form incorporating multiple $\lambda/4$ transformers. End-feeding of tiers by tapping at one-wavelength intervals along a transmission line (which reduces the cost and complexity) would not have given an adequate performance and so could not be used.

(6) TOWER AND AERIAL SYSTEM

(6.1) Tower Design

The restriction of the site area to two acres necessitated a self-supporting tower for the aerials. The tower (see Fig. 1) consists of a support structure, 440 ft high, of square cross-section, tapering from 120 ft side at the base to 14 ft at the top, and above this, three parallel-sided sections of 9 ft 6 in, 6 ft 6 in, and 4 ft 4 in in width, each approximately 72 ft high. Short tapered sections interposed between these sections of different width bring the total height to 668 ft. Each leg is supported by piled foundations. All the steelwork is galvanized, and the total weight of the structure is approximately 450 tons. An electrically operated hoist is provided between the ground and the top of the support structure.

The tower has been designed to withstand a wind velocity of 88 m.p.h. at 100 ft above the ground, increasing to 113 m.p.h. at 600 ft, with a $\frac{1}{2}$ in coating of ice.

Because of the magnitude of the tower and its prominent position on the South London skyline, the design had to take account of aesthetic values and meet with the approval of the Royal Fine Art Commission. An outline design, approved by the Commission in 1953, formed the basis of a detailed design which was approved in 1954, after a modification to part of the bracing system had been made to meet the wishes of the Commission. The approval of the Kent County Council and the Penge Urban District Council had also to be obtained.

(6.2) Aerial System: Design and Construction

After preliminary consideration it was decided to use dipoles as the radiating elements for both halves of the aerial system, to utilize their advantages of simple construction, a fairly low wind load and a relatively short development time.

Initially, model tests at one-tenth scale (at 450 Mc/s) were carried out to arrive at an arrangement of the dipole radiating elements which would give a satisfactory horizontal radiation pattern for each half of the aerial. The investigation was directed towards determining both the phase relationship of the currents in the elements and the number of elements required in a tier, since these factors must be known before the detailed design of the elements themselves can start.

It was realized, of course, that the quadrature phase relationship of radiating element currents used at the high-power regional stations had advantages. When used in conjunction with a power-sharing transformer, this system can be arranged to give a bandwidth considerably greater than that of the individual radiating elements. On the other hand, if the elements of a tier are arranged to carry co-phased currents, the bandwidth of the whole aerial system is substantially that of a single element, and hence more stringent requirements for the impedance characteristic of a single element have to be met.

The large cross-section of both supporting sections of the tower precluded a sufficiently omni-directional horizontal radiation pattern being obtained with a quadrature phase relationship, and so advantage could not be taken of the impedance-correcting properties of this arrangement. (It should be noted that the cross-section of the supporting structures at the high-power regional stations is only 1 ft 6 in × 1 ft 6 in.) It was therefore necessary to concentrate on the design of dipole radiating elements having a good impedance/frequency characteristic over the band. This requirement was made the more difficult to meet by the fact that the frequencies for Channel 1, in which the Crystal Palace station operates, are the lowest in use for television in this country.

Experiment showed that satisfactory horizontal radiation patterns could be obtained with co-phased tiers, although the large disparity in the cross-sections of the two supporting structures necessitated different arrangements for the two halves of the aerial. For the upper half an arrangement of four dipoles per tier, with one dipole mounted $0{\cdot}2\lambda$ from each face of the supporting structure, gave an acceptable horizontal radiation pattern; for the lower half an arrangement of eight dipoles per tier, with two dipoles on each face spaced $0{\cdot}5\lambda$ apart and $0{\cdot}2\lambda$ from the supporting structure, gave an acceptable result.

Since only one dipole per face per tier was required for the upper half of the aerial, it was decided that each of these dipoles should be designed as a single element. For the lower half of the aerial, however, where two dipoles per face per tier were required, it was decided that an element comprising two dipoles fed by a common concentric feeder should be developed. Each tier of the composite aerial is thus composed of four elements, one on each face of the tower, an element consisting of one dipole for the upper half of the aerial and two dipoles for the lower half. With this arrangement, the same number of aerial outlets is required on both the upper and lower halves of the distribution feeder system, and some measure of standardization of the design and components is possible.

(6.2.1) Single Dipole Element for Upper Half of Aerial.

The conductance presented at the centre of a resonant half-wave dipole is reasonably uniform over a band of frequencies determined by the thickness of the dipole limbs, while the susceptance has a negative slope over the band. By mounting the dipole on a $\lambda/4$ short-circuited stub which has a positive susceptance slope, the total susceptance may be made fairly constant over the band. Such a stub may also be used as an unbalance-to-balance transformer by running a coaxial feeder through the short-circuit, the outer of the feeder being bonded to one limb of the stub and the inner to the opposite limb at the driving point. Since the driving-point impedance of a single dipole is about 70 ohms, a standard type of feeder can be used. The position of the driving point on the stub controls the conductance presented to the feeder, and the position of the dipole on the stub controls the slope of the compensating susceptance. The mean susceptance can be controlled by the position of the short-circuit on the stub.

The final design of the full-scale dipole element (Fig. 5) was based on the principles just described. The limbs are skeletonized in the form of pyramids to give a low wind load and good structural stability, and their length can be varied by means of the adjustable tubes protruding through the end-plates. The open-ended part of the stub has been replaced by an adjustable coaxial capacitance, in order to improve the dipole structure

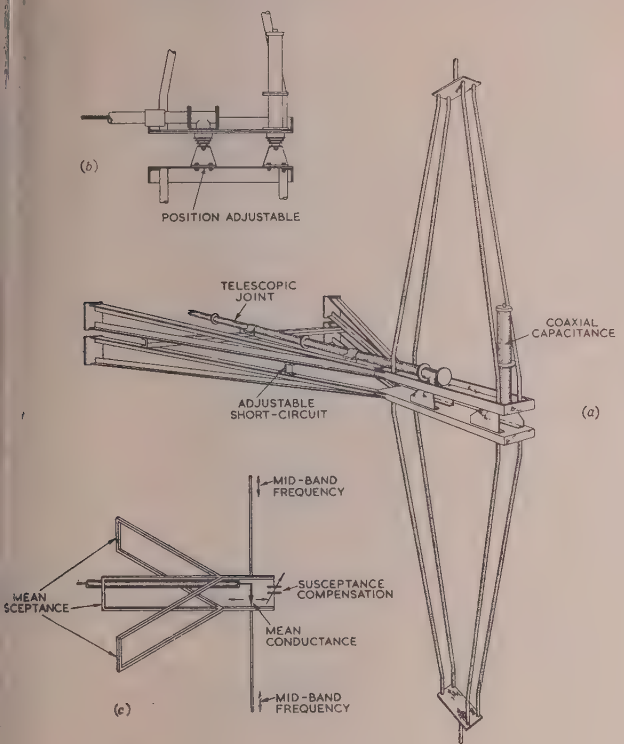

Fig. 5.—Single-dipole element for upper half of aerial.

(a) General arrangement.
(b) Detail of feed point.
(c) Impedance-adjusting controls.

nechanically, and the short-circuited part is split into three, the uter arms forming the means of mechanical attachment to the nast. Thus there are effectively three short-circuited lines in arallel.

The following controls are available for adjusting the mpedance:

(a) The length of the limbs, which controls the mid-band frequency and hence allows the bandwidth characteristics to be suitably adjusted relative to the vision carrier frequency.

(b) A movable driving-point tap incorporating a telescopic length of 2 in-diameter copper feeder, which allows the mean conductance to be adjusted.

(c) The coaxial capacitance, which controls the susceptance compensation.

(d) The three sliding short-circuits for adjusting the mean susceptance; the two outer short-circuits were fixed after preliminary tests, and fine adjustments were carried out on the centre one.

In order to prevent the radiation pattern and impedance haracteristic of the aerial from being influenced by the presence f feeders, ladders and other metalwork inside the tower, screenng conductors have been provided on each face of the tower.

5.2.2) Double Dipole Element for Lower Half of Aerial.

The conductance presented at the centre of a resonant folded alf-wave dipole varies with frequency in a manner similar to hat of a simple dipole with limbs of cross-sectional area equivaent to that of the folded limbs, but the impedance is four times reater. In addition, the transmission lines formed by the folded mbs behave in a manner similar to the support stub in a simple ipole arrangement and give a measure of susceptance compensaion, although this is not sufficient to give the optimum bandwidth realizable from the dipole and some additional compensation is necessary. In short, a folded dipole can be arranged to have a driving-point impedance of about 280 ohms and an admittance bandwidth equal to that of a simple compensated dipole of equivalent limb thickness.

The double dipole element developed for the lower half of the aerial is illustrated in Fig. 6. It consists of two folded dipoles

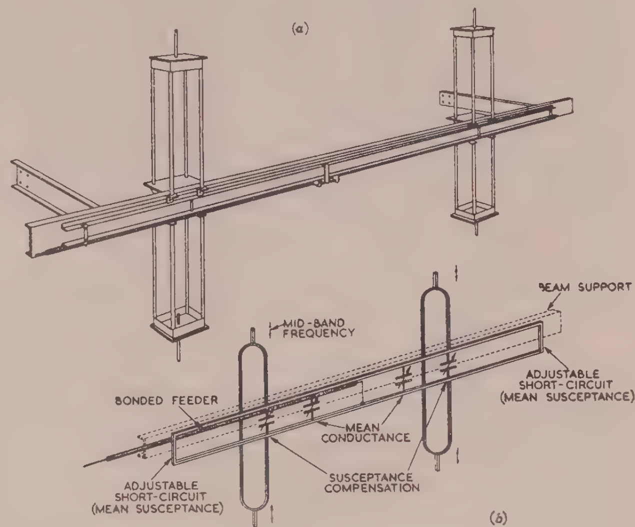

Fig. 6.—Double-dipole element for lower half of aerial.

(a) General arrangement.
(b) Theoretical arrangement showing impedance-adjusting controls.

connected by a balanced transmission line having a characteristic impedance of approximately 200 ohms. This line is approximately $\lambda/2$ long and is driven at its centre point. Seen from this central driving-point, the impedance of each folded dipole is transformed by the section of balanced line to an impedance of 140 ohms, and the two halves together thus give a driving-point impedance of 70 ohms. As with the upper half of the aerial, a standard 70-ohm coaxial feeder can therefore be used; however, the balanced line forms the balance-to-unbalance transformer, the coaxial cable being run along one conductor. To provide the additional susceptance compensation required, the balanced line is extended beyond each dipole and then short-circuited, and variable capacitance plates are connected across each dipole.

The folded dipoles and the balanced line are mounted on a horizontal beam, which is electrically dead and is attached to the tower legs at its ends by outriggers. On the front of the beam two light angles are mounted on insulators; these form the balanced line connecting the folded dipoles and are extended beyond them to form the short-circuited compensating stubs. The compensating capacitances consist of plates connected across the balanced line at the dipoles. Other plates, attached to the balanced line mid-way between the dipoles and the driving point at the centre, provide conductance adjustment. The folded dipole elements are skeletonized, being composed of four tubes, two for each limb of the fold, and have extension pieces to allow the length to be adjusted.. There are four impedance-adjusting controls, similar to those for the single dipole aerial above, except that capacitance plates are used to provide adjustment of the mean conductance and susceptance compensation, instead of a movable driving-point tap and coaxial capacitance. In the same way as for the upper half of the aerial, the tower is screened by conductors running down each face.

(6.3) Aerial Performance

(6.3.1) Gain.

The maximum theoretical gain that can be realized for an 8-tier aerial is 9·6 dB. This gain is obtained with the centres of adjacent tiers spaced 0·95λ apart, and is largely independent of the vertical radiation pattern of a single tier. At the vision carrier frequency, where the greatest gain is required, the optimum tier spacing would therefore have been 21 ft. The gain decreases very slowly, however, with decrease of tier spacing, and is affected very little by a relatively large gap in the centre of the aerial, as shown in Fig. 1. In the interests of economy in the design of the structure it was therefore decided to adopt a spacing of 18 ft between tiers for the upper half of the aerial. For the lower half, however, where structural restrictions on the height of the aerial are not important, a spacing of 20 ft was adopted. This arrangement gives a theoretical gain of 8·7 dB, but the effective gain of the system is, of course, less than this, owing to losses in the feeders and other causes, as shown in Table 2.

Table 2

	dB
Intrinsic gain of aerial (i.e. gain with perfect phasing and loss-less feeders)	8·7
Loss in distribution feeders	0·1
Loss in main feeders	0·45
Loss in combining units and vestigial-sideband filters	0·05
Net gain	8·1
Allowance for loss of gain due to mechanical and electrical asymmetries	0·2
	7·9

This corresponds to an overall power gain factor of 6·2. The gain referred to is the r.m.s. gain in azimuth relative to a half-wave dipole.

(6.3.2) Bandwidth.

Preliminary experiments carried out under stringent conditions indicated that a satisfactory performance as regards the generation of delayed image signals is most readily obtained if the aerial is matched accurately at the vision carrier frequency. The impedance of the aerial, however, cannot be allowed to deviate too far from the characteristic impedance of the main feeders at the extremities of the vision band, particularly if the possibility of colour transmission is envisaged.

The experiments showed that the following performance specification would need to be met for monochrome transmissions:

(*a*) The match at the vision carrier frequency should be such that the reflection coefficient on the main feeders would not exceed 1%.

(*b*) For double-sideband transmission the match over the sidebands should be such that the reflection coefficient measured on the main feeders should not exceed a figure increasing linearly from 1% or less at the vision carrier frequency up to 8% at 42 and 48 Mc/s. With a vestigial-sideband system, however, this specification need only be met over the lower sideband, and the reflection coefficient over the upper sideband can be allowed to increase so that it does not exceed a figure increasing linearly from 1% or less at the vision carrier frequency up to 20% at 48 Mc/s.

Another factor which had to be borne in mind was that the match at the sound carrier frequency could not be allowed to introduce a reflection coefficient of more than 15%, since anything greater than this might affect adversely the performance of the combining units.

For an in-phase aerial system the bandwidth of the whole aerial is largely governed by the bandwidth of a single element, and it is not possible in practice, even after compensation, to have a sufficiently thick dipole to meet comfortably the specified requirements for double-sideband operation. The required performance for vestigial-sideband operation, however, can be comfortably satisfied with the dipole arrangements described.

If a colour system in Band I were operated from the Cryst Palace, the chrominance carrier could be located either at t lower end of the vision band or in the space made available the upper sideband by vestigial-sideband operation. The refle tion coefficients of the complete aerial system will be of the ord of 7 and 10% respectively in these two regions, and it may found necessary to improve the aerial match at the chosen chrom nance frequency. Additional controls are provided on the ma feeders which will enable the aerial system to be matched at bo the luminance and chrominance carriers should field tes indicate that this is necessary. This matching at two frequenci simultaneously will, however, cause some degradation of t performance of the aerial for monochrome pictures, but even if very good match is required at the chrominance carrier, t degradation of the monochrome picture will be tolerable a unlikely to be observed by the average viewer.

The impedance lining-up of the aerial must be carried out wi the two halves connected in parallel, so that the mutual imp dances reflected into each half are the same as for norm operation. It follows that in the event of a breakdown of o half of the aerial, or its associated feeder, the working half w operate in a mismatched condition, so that the delayed-ima radiation will be increased in amplitude. Furthermore, a sign will be coupled into the idle half of the aerial and, after twi traversing the idle feeder, will give rise to an additional com ponent of the delayed-image signal. As a result of these effect the delayed-image radiation will be increased from 1 approximately 4%. This degradation is, however, consider tolerable under temporarily reduced power conditions. If colour system were introduced, working on one half of the aeri would cause some degradation of the received picture. A fu investigation of this problem has not yet been carried out, b preliminary estimates indicate that the effect would not be su as to degrade the received picture to any great extent.

(6.3.3) Horizontal Radiation Pattern.

It is difficult in practice to measure the horizontal radiati pattern of the complete aerial, but fortunately the measuremen made on one-tenth scale models of the upper and lower halv give the result for the final full-scale aerial to a sufficient degr of accuracy. Owing to the different form of the tiers in the tw halves, the patterns differ, that of the lower half being the mo circular because it has twice the number of dipoles per tier. T two radiation patterns are shown in Fig. 7, together with t

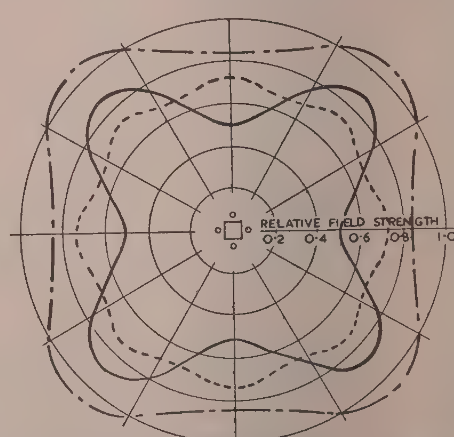

Fig. 7.—Horizontal radiation patterns of the aerial.

——— Upper half of aerial.
------- Lower half of aerial.
·-·-·- Upper and lower halves combined.

combined pattern of the complete aerial with the phasing of the two halves arranged to give the optimum r.m.s. gain in azimuth and the most uniform horizontal radiation pattern.

(6.3.4) **Vertical Radiation Pattern.**

The different forms of the upper and lower halves of the aerial system result in their having vertical radiation patterns differing in amplitude and phase. Furthermore, the distance of the dipoles from the centre of the tower is appreciably different in the two halves of the aerial, so that their contributions to the distant field would not be in phase if they were all fed with co-phased currents. It is therefore necessary to feed the two halves of the aerial with currents having a controlled phase difference, the value of which will be determined experimentally, but which will probably be about 60°. This, together with the differences in amplitude and phase variation of the vertical radiation patterns, results in a pattern for the complete aerial that varies with azimuth. Fig. 8 is a typical diagram showing the relative field strength near the base of the tower; it will be seen that there are a number of minima in this area. The distances at which these minima occur will vary with the vision modulation frequency, and this might result in viewers living very near the station receiving a distorted signal. In the final aerial design, means will be provided for advancing or retarding the phases of one or more of the aerial tiers to reduce the depth of these minima. Should it prove necessary to do this, a small loss of aerial gain, not exceeding 0·4 dB, will result.

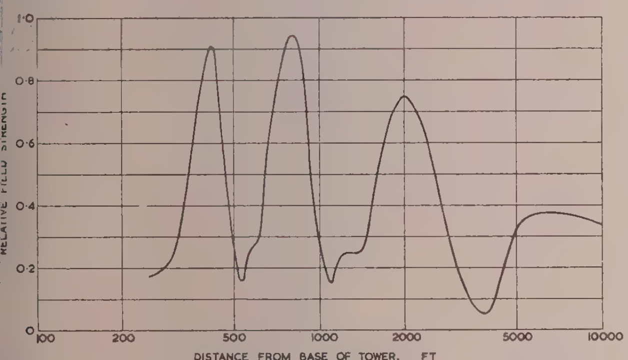

Fig. 8.—Typical diagram of relative field strength near base of tower.

It is possible that, even after this has been done, difficulties will arise if colour transmissions are radiated from the aerial. Until field tests have been carried out, however, the magnitude of these difficulties and the extent to which they may affect colour reception very close to the station cannot be assessed.

(6.4) Operation of Split-Aerial System

With two separate chains of transmitting equipment, extraneous phase changes are liable to occur between the currents in the two halves of the aerial. For the sake of simplicity, the transmitter phasing equipment is arranged to keep the inputs to the combining units in phase, and thus any of the components beyond this point in either chain may introduce a differential phase change between the two halves of the aerial. In practice, dephasing can arise only from phase-delay differences in the combining units and differential expansion of the main feeders. The worst case of dephasing due to the combining units will occur when one unit has reached its operating temperature and the other has only just commenced operation and is still cold, but the phase difference will not exceed 5° at the sound carrier and 1° at the vision carrier frequency. Calculations show that the phase change due to differential expansion of the main feeders will not exceed 2°; the total phase difference which can occur will therefore not exceed 3° at the vision carrier frequency and 7° at the sound carrier frequency.

The dephasing between the two halves of the aerial will not affect adversely the radiated signal for either monochrome or colour transmissions. For monochrome, dephasing reduces the aerial gain but has no other ill-effects, and in any case, a considerable tolerance is permissible. For example, a phase difference of 40° will result in a reduction in gain of only 0·5 dB, so that the amount of dephasing likely to occur in practice will cause a negligible reduction in gain. Dephasing will also cause changes in the field strength near the station, owing to a shift in the positions of the minima in the vertical radiation pattern, but since the field in the minima will tend to be increased, conditions close in will, if anything, be improved, although the effect will be very small.

For colour transmissions, so far as the distant field is concerned, dephasing will result in a change in the relative levels of the luminance and chrominance signals, but even with the maximum dephasing liable to occur, it will be too small to be of any importance. Very near the station, the effect of dephasing is more difficult to assess; although the field pattern will change slightly, there is no reason why reception should be less satisfactory with dephased aerials than with correctly-phased aerials.

The foregoing remarks apply, of course, only to the vision signal; for the sound signal, the effect of dephasing is merely a negligible reduction in gain.

(7) ACKNOWLEDGMENTS

The authors wish to thank the Director of Technical Services of the BBC, under whose guidance the work described was carried out, for permission to publish the paper. They also wish to express their appreciation of the work of their colleagues throughout the Engineering Division of the BBC, and their appreciation of the close co-operation of Marconi's Wireless Telegraph Co. and of British Insulated Callender's Construction Co.

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[The discussion on the above paper will be found on page 663.]

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Mar. 19

THE BROADCASTING HOUSE – CRYSTAL PALACE TELEVISION LINK

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SUMMARY

The initial requirement for the Broadcasting House–Crystal Palace Television link is for one channel in each direction, but it is likely that a second channel will be needed later. The transmission of two programmes over a single tube would make 0·975 in coaxial cable economic over this distance of 9 miles and would permit transmission between terminals without intermediate equipment. To meet the need of good performance with simple low-cost equipment, a double-sideband system with amplitude modulation has been developed. To allow for later development, e.g. a wider-band channel for colour, the carrier frequency of the monochrome channel has been placed at 15 Mc/s.

In the transmitting terminal the video signal is translated into the band for transmission over the cable, and in the receiving terminal the incoming signal is corrected for the loss, attenuation and delay distortions which occur in transmission, and the video signal is recovered. The performance of the link is given in terms of the measured amplitude and differential delay characteristics, transient response, linearity and signal/noise ratio.

(1) INTRODUCTION

The methods of providing long-distance point-to-point television links and temporary links have been dealt with in a number of papers and were summarized in two Television Convention papers.[1] In all these cases the aim was to provide a single programme link for one-way or two-way transmission.

On long-distance coaxial-cable circuits the video signal of 3 Mc/s bandwidth has to be translated up in the frequency band by modulating a carrier wave, and to economize in bandwidth, vestigial rather than double sideband transmission is usually employed. This complicates the terminal equipment, but for this type of circuit it represents a relatively small proportion of the total cost. A further consideration is that vestigial-sideband operation inevitably introduces some non-linear distortion unless complicated methods of detection are employed, and it may impose severe balance requirements on the modulators. The long-distance technique has been used for some of the shorter links, e.g. Wembley–Broadcasting House and Lime Grove–Broadcasting House, since plant was available at the time of provision.

For short links video-frequency transmission over balanced-pair or coaxial cables can be used, but there is always a danger of low-frequency induction causing interference with unbalanced circuits. Balanced-pair circuits involve conversion from unbalanced to balanced operation.

To provide efficient and economical links for varying lengths of circuits, different transmission systems are required. For short-distance circuits there is a need for simple low-cost equipment of good performance, since several links may be operated in tandem. The distance of 9 miles between Broadcasting House and Crystal Palace is too long to employ direct video transmission conveniently, and the attenuation of 0·375 in coaxial cable would require the use of intermediate repeater equipment. However, the more expensive 0·975 in coaxial cable would b economic in the likely event of the transmission of two pr grammes over a single tube and would permit direct transmissic between the terminals without intermediate equipment. Mor over, since it is proposed to use the Crystal Palace site as a pick-u point for television outside broadcasts, a vision circuit will als be required for carrying these signals to the Broadcasting Hous switching centre for connection to the main television networ To meet these needs the Post Office agreed to provide tw 0·975 in coaxial tubes between Broadcasting House and th Crystal Palace,[2] the BBC providing the terminal equipment.

For a high-quality circuit of this type it was considered th the simplicity and performance of a double-sideband tran mission system outweighed the advantage of saving in bandwidt obtainable with the more complex vestigial-sideband equipmen The same system is likely to find application for other short link and can be used on 0·375 in coaxial cable where the distance do not exceed about 3½ miles.

(2) TRANSMISSION PERFORMANCE SPECIFICATION

A link of this type should absorb very little of the permitte overall distortion between studio and transmitter; the followin requirements were therefore laid down:

Amplitude frequency response:	±0·15 dB up to 1·5 Mc/s. ±0·25 dB up to 3 Mc/s.
Group delay:	From 100 kc/s to 3 Mc/s the dela distortion should not excee ±0·025 microsec.
Linearity:	For linearity measurements the ou put of the system should b adjusted to 1 volt with a standar 1-volt input television wavefor corresponding to peak white.
Picture:	Under the above conditions the rat between the input and outpu picture signals should be constan within ±3% for all values fro black to peak white.
Synchronizing pulses:	The ratio between the input and ou put synchronizing-pulse ampl tudes should be unity to withi ±5% for all values of pictu signal between black level an peak white. The system should be capable o handling a 50% increase in vide signal without serious distortio
Transient response:	With a test signal consisting of rectangular pulse having a ris and fall time of 0·1 microsec th overshoot should be less than 5 of the pulse amplitude with ringing frequency of 3 Mc/s o above. With a line-bar waveform of varyin widths the variation in the ou put level over the bar should b less than 2% of the bar amplitud

Dr. Rendall and Mr. Padel are with the British Broadcasting Corporation.

Low-frequency response: With a 50 c/s square wave the variation in the output level over a half-cycle should be less than 5% of the d.a.p.

Noise: The d.a.p. picture/noise ratio should be 43 dB (for the proposed frequency allocation the noise has an essentially flat frequency spectrum).

3) CHOICE OF CHANNEL AND FREQUENCY LOCATION

Since a decision regarding colour standards is some way off, he first channel was designed for normal monochrome transnission with a bandwidth of 3 Mc/s, and in order to leave as great a bandwidth as possible for future development, the arrier frequency of the system was placed as high as was conistent with obtaining the required signal/noise ratio. A heoretical investigation of signal/noise ratio with a system bjective of 43 dB [(d.a.p. picture)/(d.a.p. noise)] was made, aking into account the output power obtainable over the equired bandwidth with available valves, the loss introduced by he cable and the noise factor of the receiving amplifier. It was hown that this signal/noise ratio could be achieved for the cable nsertion loss with a double-sideband amplitude-modulated ystem having a modulation depth of 0·7 on a peak-white video ignal and with a carrier frequency of 15 Mc/s. The spectrum elow about 11 Mc/s is thus available for further development. Positive modulation is employed.

The carrier levels given in the paper are in volts r.m.s. correponding to peak-white modulation.

mid-point of the input transformer. The video signal, at about 0·5 volt d.a.p., is connected between this point and earth and an adjustable direct voltage is applied between the mid-point of the output transformer primary and earth, this point being decoupled at carrier-signal frequencies with a series-resonant circuit. The level of the carrier at the output, and hence the modulation depth, is adjusted by varying this potential relative to earth, and on a peak-white signal with the 0·7 depth of modulation used the output from the modulator is about 160 mV r.m.s. Unwanted higher-frequency products from the modulator are removed by a low-pass filter which is separated from the former by a pad.

The low-level carrier signal from the filter is then passed through the terminal-equipment delay corrector. This network requires resistance terminations which are constant over the modulated carrier band, and it is convenient to incorporate it in the sending terminal because gain is available for making good the loss in the pads between which it operates. The signal level is then raised in a carrier amplifier, which delivers 3 volts r.m.s. to the cable, corresponding to a power of 0·12 watt.

The carrier amplifier, as well as being part of the sending equipment, is also used at the receiving terminal to make good the signal loss occurring on the cable, and accordingly the signal/noise ratio of the system depends directly on the performance of this amplifier. At the transmitting terminal it sets an upper limit to the power which can be delivered to the cable, while at the receiving terminal the amplifier noise sets a lower limit to the input signal for a given signal/noise ratio.

The performance of the input and output coupling networks of the amplifier is controlled according to Bode's resistance

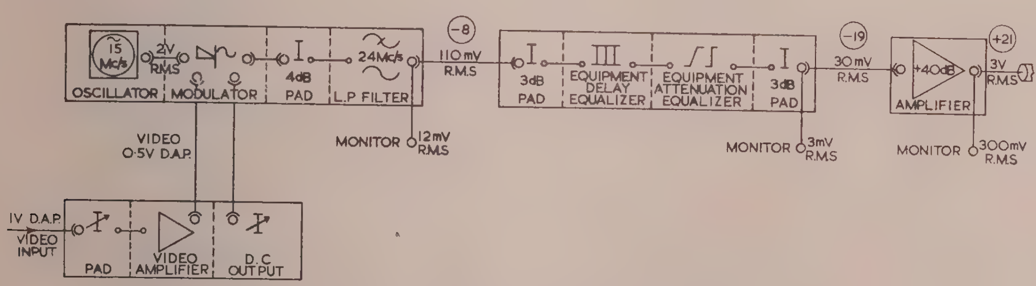


Fig. 1.—Schematic of transmitting terminal.

All carrier levels are r.m.s. values corresponding to peak-white modulation. Power levels are in decibels relative to 1 mW into 75 ohms.

(4) TRANSMITTING TERMINAL EQUIPMENT

The sending terminal equipment (Fig. 1) translates the video ignal into the band for transmission over the coaxial cable.

The video signal to be transmitted is received at the standard evel of 1 volt d.a.p. It is raised in a video feedback amplifier to bout 5 volts d.a.p. and the black level of the signal is then lamped; the video output, which now contains a d.c. component, s taken directly from the cathode of the clamped valve to the nodulator. The clamp, which gives a choice of three timeonstants, can alternatively be switched out and d.c. restoration on the tips of the synchronizing pulses used. For test purposes he system can be switched to an a.c. condition.

The modulator[3] consists of a ring of germanium-crystal diodes. Generated by a 15 Mc/s crystal oscillator, the carrier is supplied o the modulator at about 2 volts r.m.s. via an isolating pad and wide-band input transformer. The input and output transormers are designed as 2-section networks with a Chebŷshev esponse[4] to have a deviation of less than 0·15 dB over the band. A carrier balance of better than 35 dB relative to the carrier with peak-white modulation can be obtained by a simple d.c. selection est for the crystals and an adjustment of a potentiometer at the

integral theorem[5] by the input and output capacitances. These in turn are set by the capacitances of the available valves, the figure of merit of which is a controlling factor in the amplifier gain and feedback which can be achieved.

The amplifier provides input and output terminations for the cable with a maximum reflection coefficient of 0·17 over the band of the modulated carrier signal, using a 2-section network giving a Chebŷshev response. The input transformer steps the 75-ohm cable impedance up to 2 500 ohms, the high-side inductance tuning with the input capacitance of the first CV138 valve, which is a cathode-follower. The subsequent three valves, two CV138 and the output CV2127, form a 3-stage feedback amplifier.[6] The first two inter-stages are damped tuned circuits, and the feedback network, which is common to the first and output valve cathodes, consists of a resistor in series with a series-resonant circuit, tuned—like the input, output and inter-stage networks—to the geometric mean frequency of the pass band. Variation of the input admittance of the first stage of this 3-stage amplifier over the frequency band was too large to provide a satisfactory termination for the input coupling network, and a cathode-follower buffer stage was used in order to give this. In the anode

circuit of the output valve the output coupling network is of similar type to the input, the high-side impedance of 1 500 ohms being stepped down to provide a termination for the cable.

The amplifiers, which are adjusted on test to have a flat frequency response within $\pm 0{\cdot}1$ dB from 12 to 18 Mc/s, have a forward gain with feedback of 40 dB, and there is some 40 dB of feedback at the mid-band frequency, falling to about 16 dB

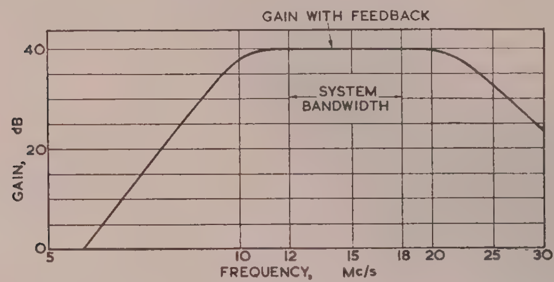


Fig. 2.—Amplitude/frequency response of carrier amplifier.

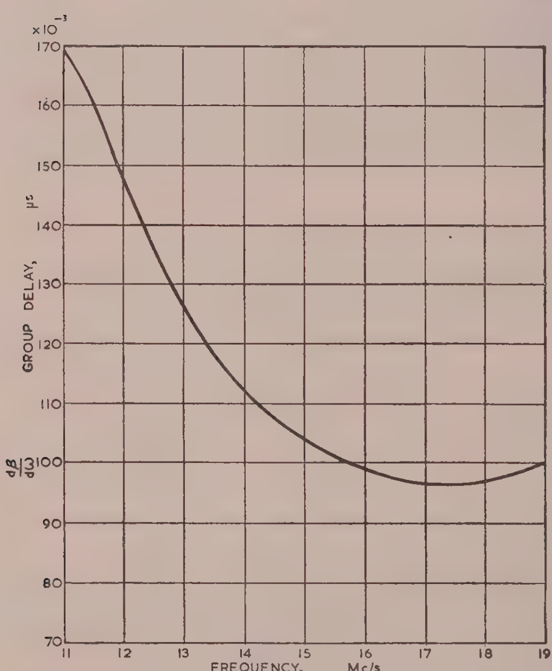


Fig. 3.—Group-delay/frequency response of carrier amplifier.

at 12 and 18 Mc/s. The amplitude/frequency and uncorrecte delay/frequency responses are shown in Figs. 2 and 3 respe tively.* The low-frequency cut-off of the amplifier is the mai source of the delay distortion in the system. The amplifier nois factor is about 6 dB, and the linearity is such that it will handl a signal level 6 dB above normal without serious overloading.

The electrical performance of the amplifier depends closely o the mechanical layout, component position, wiring and earthing and considerable attention has been given to these factors i arriving at the final design. It is constructed in a box whic clips on to the sub-panel of a standard 19 in panel with the valve protruding through holes in the sub-panel. Signal connection are made with U-links to coaxial plugs mounted on the sub panel, and a potentiometer across the output gives access fo monitoring. Power, from a stabilized supply unit, is fed throug a multi-way plug and socket which connects when the amplifie unit is in position. Special attention has been given to factor affecting reliability and stability, including the choice of com ponents, ventilation and temperature rise, which has been kep within safe limits without forced ventilation.

(5) RECEIVING-TERMINAL EQUIPMENT

The receiving terminal (Fig. 4) corrects the received signal fo the loss, attenuation and delay distortions and subsequentl recovers the video signal.

The loss of the $8{\cdot}84$ miles of coaxial cable is $53{\cdot}5$ dB at th carrier frequency for a nominal cable temperature of 10° C The $6{\cdot}3$ mV input signal available is raised in the first carrie amplifier to approximately 630 mV before equalization. Th selectivity of the amplifier input circuit removes any low-frequenc interference coming from the cable.

The difference in cable attenuation between 11 and 19 Mc/s about 15 dB. Two fixed attenuation equalizers correct th distortion corresponding to 4 and $4{\cdot}5$ miles of cable respectivel the configuration of these equalizers being shown in Fig. 5. A variable equalizer corrects the remaining $0{\cdot}4$ mile, togeth with the seasonal change in attenuation with temperature. Th equalizer is of the form devised by Bode[7] in the late 1930's, an it has already proved a powerful tool when applied to th correction of video signals, the unique feature being that it giv a series of attenuation characteristics which are closely pr portional to a given attenuation characteristic by the variatic of a single resistance element. In the constant-resistance form i which it is used, pairs of resistance elements are varied. On th maximum setting it equalizes a mile of cable, the correctic amounting to about $1{\cdot}6$ dB between 11 and 19 Mc/s, and inte mediate steps correct the cable loss to the nearest $0{\cdot}1$ mil The equalizer schematic is shown in Fig. 5B.

The fixed equalizer units are removable sub-assemblies, s

* Delay measurements were made with differential delay-measuring equipme employing a sinusoidal modulating frequency of 16 kc/s.

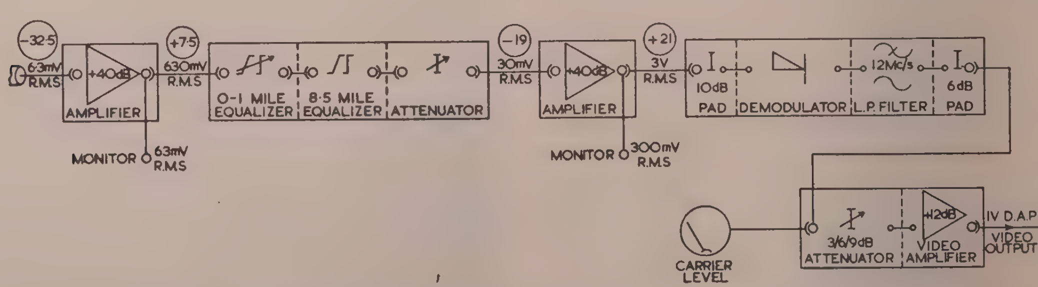


Fig. 4.—Schematic of receiving terminal.

All carrier levels are r.m.s. values corresponding to peak-white modulation. Power levels are in decibels relative to 1 mW into 75 ohms.

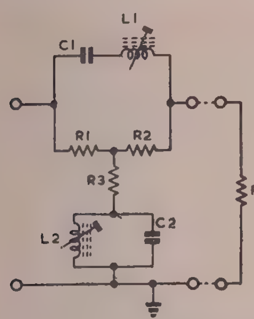


Fig. 5A.—Attenuation-equalizer section.

$L_1/C_2 = L_2/C_1 = R^2$
$\omega_0^2 = 1/L_1C_1 = 1/L_2C_2$

that sections required for any intermediate lengths of cable can be readily fitted.

The main cause of the amplifiers departing from a flat frequency characteristic over the band is the Chebyshev response of the input and output networks. Each of these networks produces a sag of about 0·1 dB around the carrier frequency relative to the edges of the band, and since the system incorporates three amplifiers and the effect is additive, there would be an overall sag of about 0·6 dB. This is a design departure, and it is the function of the equipment attenuation equalizer to correct for it.

As already mentioned, the major contribution to the delay distortion of the system is produced by the amplifiers. Since delay distortion of the sidebands relative to the carrier of a modulated signal can give rise upon demodulation to both amplitude and delay distortion (which depend upon the modulation index), the delay equalizer operates over the band of the modulated carrier signal to correct the delay distortion in the terminal equipment. It consists of four constant-resistance all-pass sections of the resonant type,[8] screened to remove unwanted coupling between sections and between the series and shunt arms of individual sections.

The unbalanced bridged-T section[9] shown in Fig. 5C allows a close approximation to the equivalent lattice, which is difficult to obtain at these frequencies. To achieve this, the windings of the coupled coil are interleaved to give a high degree of balance; the input and output connections of the section are made directly across the capacitor to keep the lead inductance as small as possible, and the symmetry of the section is closely preserved to present the same impedance at either end of the section. Each section is assembled on a small tray, and the unit is then placed in a jig box which mounts on a bridge for setting up the section. The jig box is identical with the compartment housing individual units in the delay equalizer, so that once the section has been adjusted and tested it can be transferred complete to the main equalizer. This arrangement has been found to give a reliability and consistency of results not obtainable by other means.

To obtain a smooth delay and loss characteristic for this equalizer, each individual section must present a constant impedance over the operating band. This is achieved by taking the precautions described, by careful adjustment of the sections and by proportioning the dissipation in the series and shunt

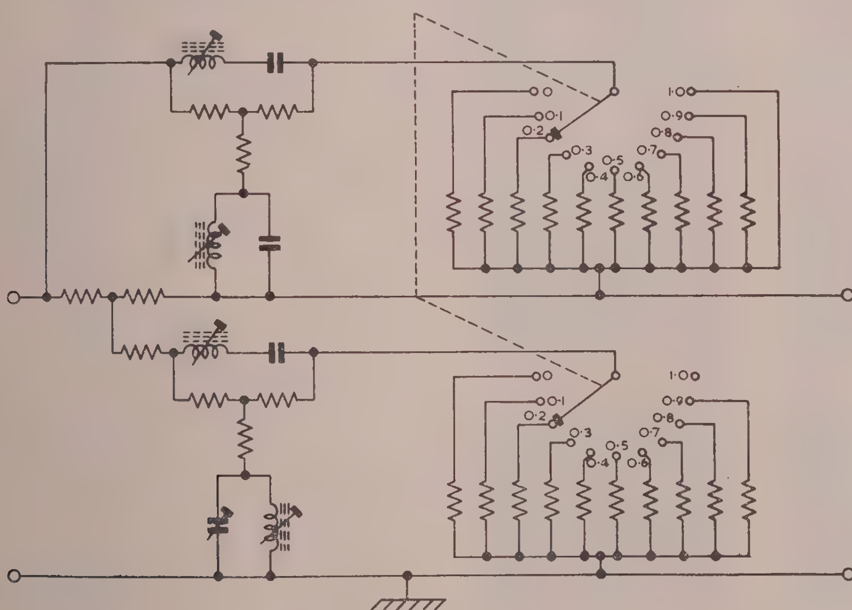


Fig. 5B.—Bode equalizer circuit.
Maximum equalization: 1 mile of 0·975 in coaxial cable. Intermediate settings give corresponding fractions of 1 mile.

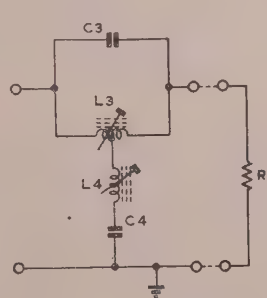


Fig. 5C.—Delay-equalizer section.

$L_3/C_4 = L_4/C_3 = R^2$
$\omega_0^2 = 1/L_3C_3 = 1/L_4C_4$

arms correctly. Since the dissipation is concentrated principally in the coils this last condition is satisfied when the Q-factors of the inductors in the individual sections are made equal.[10] Then the shape of the loss characteristic is similar to that of the delay characteristic, and the loss of the complete network can be corrected with a simple attenuation equalizer section. Each section is set up by resonating the series circuit, by adjustment of the inductance with the shunt circuit disconnected; with the shunt circuit reconnected and the section terminated in a 75-ohm resistor, the shunt inductance is adjusted for zero input reactance at the resonance frequency of the section and the measured input resistance is within 75 ± 1 ohms at this frequency. The complete network has a return loss of better than 26 dB, over the frequency band of operation, with a 75-ohm resistance termination.

The measured characteristics of the correction network and terminal equipment with correction are shown in Fig. 6A and the loss before and after equalization in Fig. 6B.

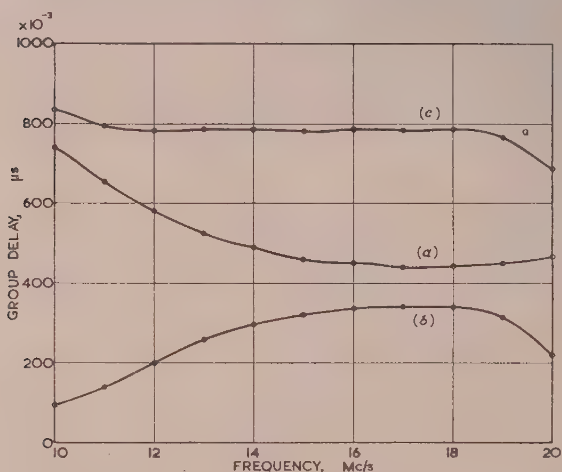


Fig. 6A.—Group delay of transmitting and receiving terminals.

(a) Without delay correction.
(b) Equipment delay equalizer.
(c) With delay correction.

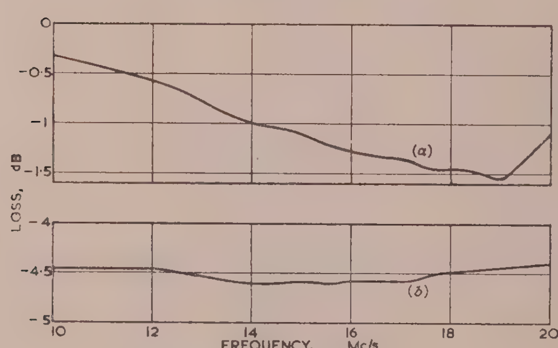


Fig. 6B.—Insertion loss.

(a) Equipment delay equalizer.
(b) Equipment delay equalizer with attenuation correction.

The cable-and-equalizer delay network consists of a single all-pass section designed to correct the residual delay distortion of the cable and the cable attenuation equalizers. Fig. 7 shows the delays.

The loss in signal through the cable equalizers is adjusted by a variable attenuator to give a level of 30 mV, which is brought up to 3 volts r.m.s. by a carrier amplifier. To terminate the latter

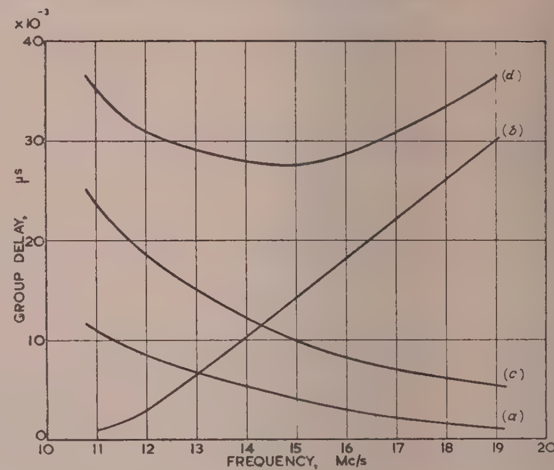


Fig. 7.—Group delay.

(a) 8·84 miles of 0·975 in coaxial cable.
(b) Attenuation equalizers for (a).
(c) Cable and equalizer delay corrector.
(d) Cable and attenuation equalizers with delay correction.

it is followed by a resistance pad, and a wide-band transforme steps up the signal level to about 2·5 volts r.m.s. for envelop detection. The full-wave detector employs a pair of germanium crystal diodes as the non-linear elements, and the mean rectifie current is indicated on a meter. The output video amplifier i fed through a low-pass filter which removes the carrier an unwanted higher-frequency components resulting from demodula tion. This 3-stage feedback amplifier, which has a gain of 12 dB gives a 75-ohm output impedance from the anode of the fina valve, and it normally delivers a video signal of 1 volt d.a.p. int a 75-ohm load.

(6) TEST EQUIPMENT

Two special units of test equipment have been developed an will be provided at the terminals in addition to the standard vide equipment normally available at BBC stations.

The first is a transmission measuring set which operates over th modulated carrier band of the system. It comprises an oscillato tunable over the range 10–20 Mc/s, a variable attenuator, standard demodulator unit and a change-over switch. As wel as being used for testing, checking and adjusting the termina equipment, the output level of 1 volt r.m.s. from the oscillato permits measurements to be made over the cable.

The second unit is for making observations and measurement of the modulated envelope, e.g. when setting the modulatio depth and also when the system is carrying picture signals. I order to avoid the cost of providing a special display oscillo graph operating over the band of the carrier signal, a frequenc conversion to a carrier frequency of 0·3 Mc/s is employed t obtain a signal for display on a video-waveform monitor. A standard modulator is used, the normal video input of this uni now giving the output display.

Since this 0·3 Mc/s carrier frequency is lower than the highe modulating frequencies, the lower-sideband frequencies firs decrease to zero frequency (corresponding to a 300 kc/s vide modulation) and then fall back in the band. The signal canno be demodulated without distortion, because of this folding back but the latter does not interfere with the observation of th display of the envelope applied to the signal plates of a waveform monitor, provided that the envelope is repetitive (so that th monitor time-base can be synchronized to it) and that a irrational relation exists between the frequency of the video signa

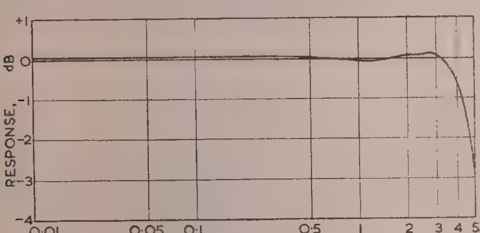
nd the 0·3 Mc/s carrier. A television signal fulfils the former, nd in practice the latter is almost always fulfilled. Difficulties an arise only if a multiple of the fundamental video frequency alls within a few cycles per second of the 0·3 Mc/s carrier requency; in these circumstances a slight shift of the local scillator frequency gives a normal display.

The carrier levels through the system can be readily measured nd set up with the monitor, which also enables a rapid check to e made when the system is carrying programme.

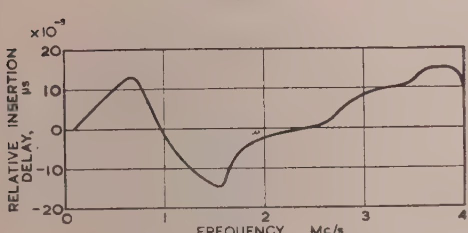
(7) PERFORMANCE OF THE LINKS

Installation of the equipment on the two 0·975 in coaxial ubes between Broadcasting House and Crystal Palace was completed early in December, 1955. One circuit has been provided n each direction, but duplicate equipment allows the return ircuit to be reversed, when it is not required for outside-broadcast purposes, to give an immediate reserve.

Measurements made over the circuits have shown good agreement with the theoretical design performance. The measured nsertion-loss and group-delay characteristics at video frequency or the link from Broadcasting House to the Crystal Palace are hown in Figs. 8(*a*) and 8(*b*) respectively. The amplitude response



(*a*)



(*b*)

Fig. 8.—Measured characteristics of Broadcasting House–Crystal Palace link.

(*a*) Insertion loss. (*b*) Group delay.

s within ±0·1 dB to 3 Mc/s and is 0·8 dB down at 4 Mc/s. The differential delay distortion is ±0·015 microsec between 100 kc/s and 4 Mc/s.

The transient response is illustrated in Fig. 9. Fig. 9(*a*) shows a 2 microsec rectangular pulse before and after transmission over wo systems in tandem connected by a video-frequency loop at he Crystal Palace. The times of rise and fall are 0·11 microsec and the overshoot is less than 5% of the pulse amplitude at a inging frequency of about 5 Mc/s. Figs. 9(*b*) and 9(*c*) show line-bar and line-sawtooth respectively, before and after transmission. Sine-squared pulses before and after transmission are shown in Figs. 9(*d*) and 9(*e*).

The linearity of the system, as defined in Section 2, gives an nput/output picture ratio which is constant to ±2%, and with he synchronizing waveform the ratio of input to output amplitudes shows a reduction in the output synchronizing pulse of ess than 5%. This occurs mainly in the demodulator and is

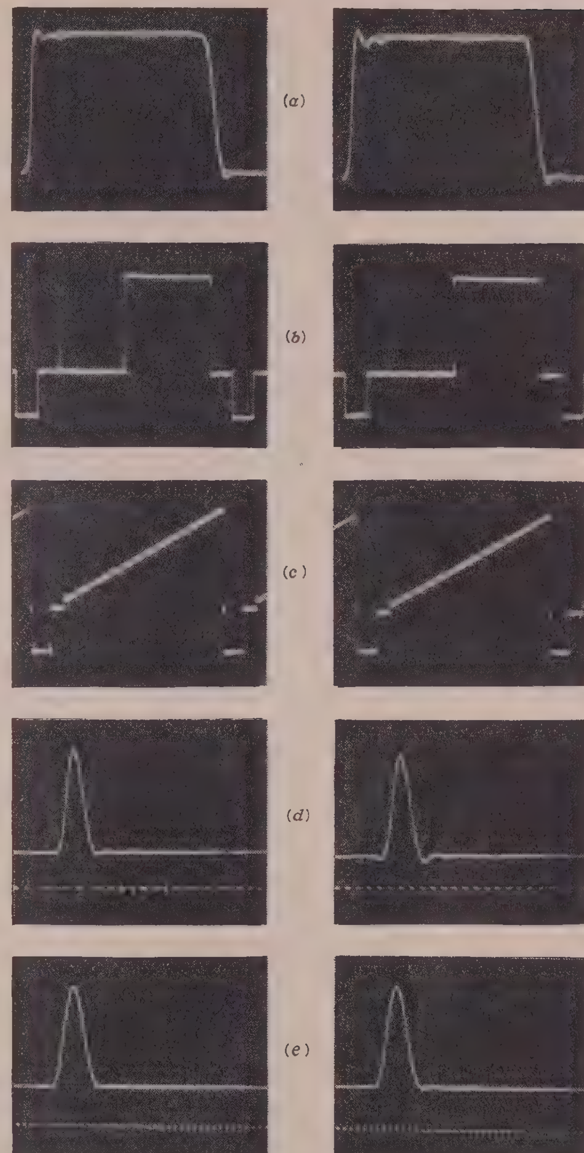


Fig. 9.—Waveforms of signals before and after transmission over two links in tandem.

Left-hand side: Before transmission.
Right-hand side: After transmission.
(*a*) 2 microsec pulse (timing marker: 1 microsec).
(*b*) Television waveform with 40 microsec line bar.
(*c*) Television waveform with line sawtooth.
(*d*) 0·17 microsec sine-squared pulse.
(*e*) 0·33 microsec sine-squared pulse.

Timing markers in (*d*) and (*e*): 0·1 microsec.

constant and independent of picture amplitude. The system will handle a 50% increase in video signal and maintain this linearity.

Measurements of random noise on a d.a.p. basis have given a picture/noise ratio of 45 dB; the picture/hum ratio is 46 dB.

(8) CONCLUSIONS AND ACKNOWLEDGMENT

The measured results which have been obtained on the link show that the system performance meets the requirement of absorbing only a small proportion of the permitted overall distortion between the studio and the transmitter. Since a

double-sideband signal is relatively insensitive to certain types of distortion compared with a vestigial one, and the equipment avoids much of the complexity of a vestigial system, it is not anticipated that undue difficulty should arise in maintaining the performance of the equipment.

The development work was carried out in the Television Transmission Section of Designs Department by a small group, whom the authors are privileged to represent. The authors would like to thank the Chief Engineer of the BBC for permission to publish the paper.

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[The discussion on the above paper will be found on page 663.]

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Paper No. 2075 R
Mar. 1956

AND I TELEVISION-TRANSMITTER DESIGN, WITH PARTICULAR REFERENCE TO THE TRANSMITTERS AT CRYSTAL PALACE

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(The paper was first received 24th January, and in revised form 15th February, 1956. *It was published in March*, 1956, *and was read before the* Radio and Telecommunication Section 4*th April*, 1956.)

SUMMARY

The paper describes television transmitting equipment designed to perate in two parallel chains to ensure reliability.

The vision transmitters are designed to work with considerable istortion and noise in the input signal, and the noise-rejection and amp circuits developed for this purpose are discussed. The use of trodes in the output stage of the vision transmitter enables receiver-ype valves to be used throughout the modulator, and permits the dvantage of high-level modulation to be exploited.

The methods of phasing of both radio and vision frequencies are escribed.

The implications of colour television on design are discussed and the neans adopted in these transmitters to assure faithful colour transmission are described.

(1) INTRODUCTION

The design of television transmitters is governed to a major xtent by the types of valve available. Previous designs[1-3] used riodes as grid-modulated amplifiers, and the difficulties of driving nd modulating these valves for the television service were overcome by expending considerable power in both the r.f. driving tages and the modulating stages. In a later design[4] some effort was made to overcome these difficulties by adopting low-level nodulation.

The relative merits of low- and high-level modulation have been discussed elsewhere,[5] and there is little doubt that, if tetrodes are available as grid-modulated r.f. amplifiers, the choice will be, wherever possible, in favour of high-level modulation.

Air-cooled tetrodes of 10 kW anode dissipation are now available, and the Crystal Palace transmitters are examples of equipment which uses these valves and has been designed to operate on any of the three more popular television standards, i.e. the 405-line British standard, the 525-line F.C.C. standard and the 625-line C.C.I.R. standard.

By the use of tetrodes throughout, the whole of the r.f. amplifier stages for a 15–20 kW transmitter can be accommodated in one cabinet 2 ft 6 in wide, 3 ft 9 in deep and 7 ft high. The modulator, together with a large amount of waveform-correction apparatus and modulator power supplies, is housed in a similar cabinet.

The positive-modulation edition of the vision transmitter has an overall efficiency of 33% on peak white.

The sound transmitter for the BBC must operate on a.m. standards which exist little outside this country. Conventional class-B modulation of the anode of the final r.f. stage is employed; the final stage uses push-pull triodes in earthed-cathode connection, since a design of this circuit existed and was used as the penultimate stage of a sound transmitter already in use by the BBC.[6]

(1.1) Preliminary Design Considerations

To increase reliability of service from Crystal Palace, two transmitters are operated in parallel—each transmitter working into mutually independent sections of the aerial system. Co-phasing of the two r.f. channels and of the two video-frequency channels is necessary and means for effecting this are described in Section 2.1.

Provision is made for switching both aerial sections to either transmitter and also for switching both transmitters to one aerial section.

Either transmitter removed from its aerial can be separately tested into a resistance load without interrupting service. In each transmitter, apart from care in generously rating all component parts, provision is made for switching out immediately all the more complicated arrangements which are included to cater for unusually bad input signals, and to provide the simplest possible chain of amplifiers as a basic minimum in case of fault, even at the expense of some performance. For example, the best possible stability of radiated black level is achieved by means of overall feedback operating in the transmitter clamp circuits; but in the event of fault the feedback can be removed, leaving a conventionally clamped transmitter in operation. Clamp-pulse failure is cared for by switching the transmitter to 'd.c. restoration'. The deterioration of performance experienced by this immediate switchover in both cases is measurable but not of such a magnitude as to cause annoyance at the receiver.

Where suspected units cannot be switched out of service, full metering of all independent current paths and full waveform monitoring facilities are provided.

Examination of BBC specifications and those of authorities in other countries reveals that, to conceive an economic vision transmitter substantially unchanged to meet the various standards, two basic editions are required, one for positive, and the other for negative, modulation. The difficulty of combining these into one edition is due to the greater peak power available from a given valve under negative-modulation conditions and the different power levels corresponding to 'black' or 'pedestal' in the television waveform. These two factors lead to rather different power supplies and operating conditions. Furthermore, for grid modulation in the negative sense the main vision-frequency amplifier is dealing with components of current corresponding to picture signals as it approaches the minimum of its current excursion. To preserve adequate reactive current-handling capability, this minimum is substantial and considerably in excess of the minimum adequate for the corresponding excursion into the synchronizing-pulse region in positive-modulation systems.

Colour television, while not yet commonly used, is sufficiently near for customers to demand that current equipment will deal with any colour system now known and likely to be operated within the life of the equipment. On the assumption that N.T.S.C. type signals will be used, we may assess the additional power requirements in the vision transmitter and design accordingly. These additional requirements are not easy to meet in the preliminary design stage. Detailed provisions will be discussed later, but it is clear that, while it is possible to meet the more stringent phase/frequency response required, it is not economically possible to design video-frequency and r.f.

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amplifiers with amplitude/phase characteristics adequate to deal with the overall requirement of only 1–2° of phase shift when the signal changes from one comparatively black to a saturated colour picture of full luminance. This difficulty is overcome partially by liberal design and more completely by precorrection circuits.

In the general engineering of this type of band I transmitter the physical separation of vision-frequency circuits into units has been determined by a general consideration of the functions and specifications of particular circuit arrangements. Where it has been possible to assign a complete identity and performance specification to a circuit arrangement, it has been designed as unit to facilitate its integration into more general application This has the advantage of giving flexibility and of partial star dardization at the expense of sacrificing overall gain per stag since, in order to achieve flexibility, it has been necessary in som cases to have both input and output signals at standard level.

The design of power supplies for high-voltage power has unde gone a significant development over the past few years. In tur mercury-vapour and selenium rectifiers have enjoyed som popularity. In the present series of transmitters the designe

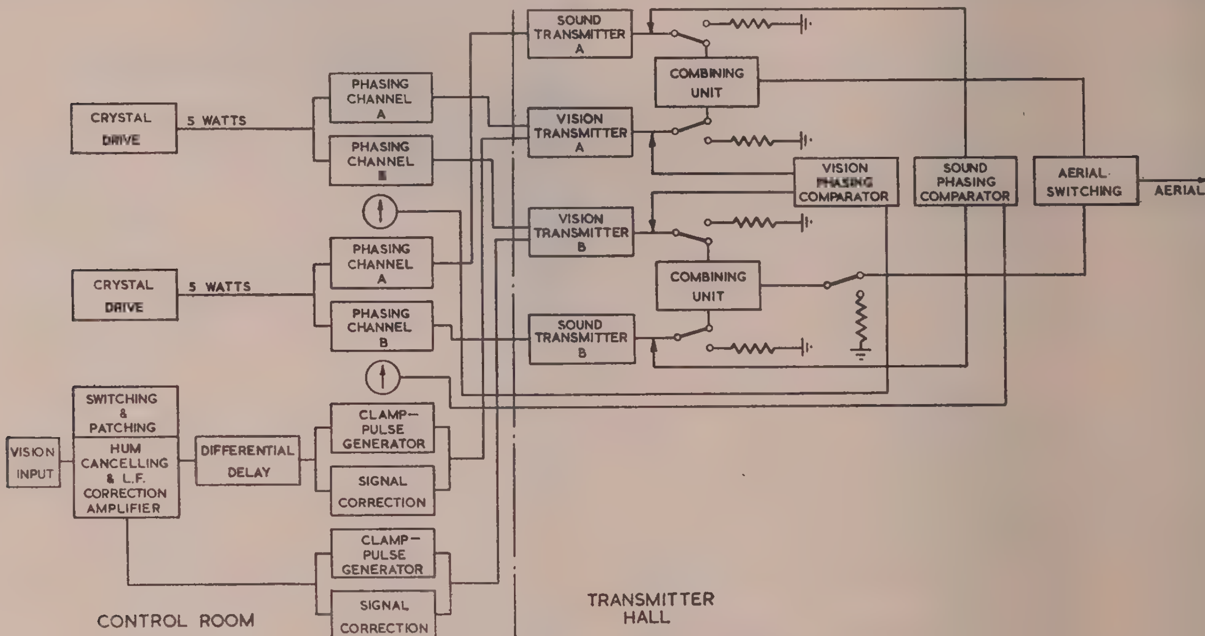

Fig. 1A.—Schematic of paralleling arrangements.

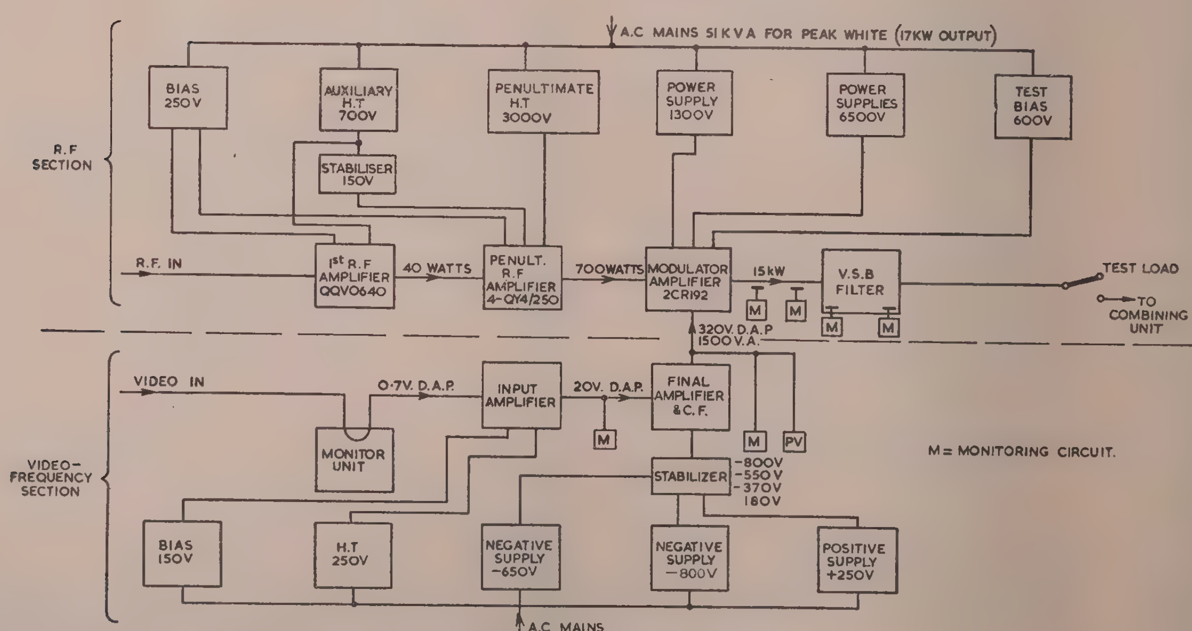

Fig. 1B.—Schematic of vision transmitter.

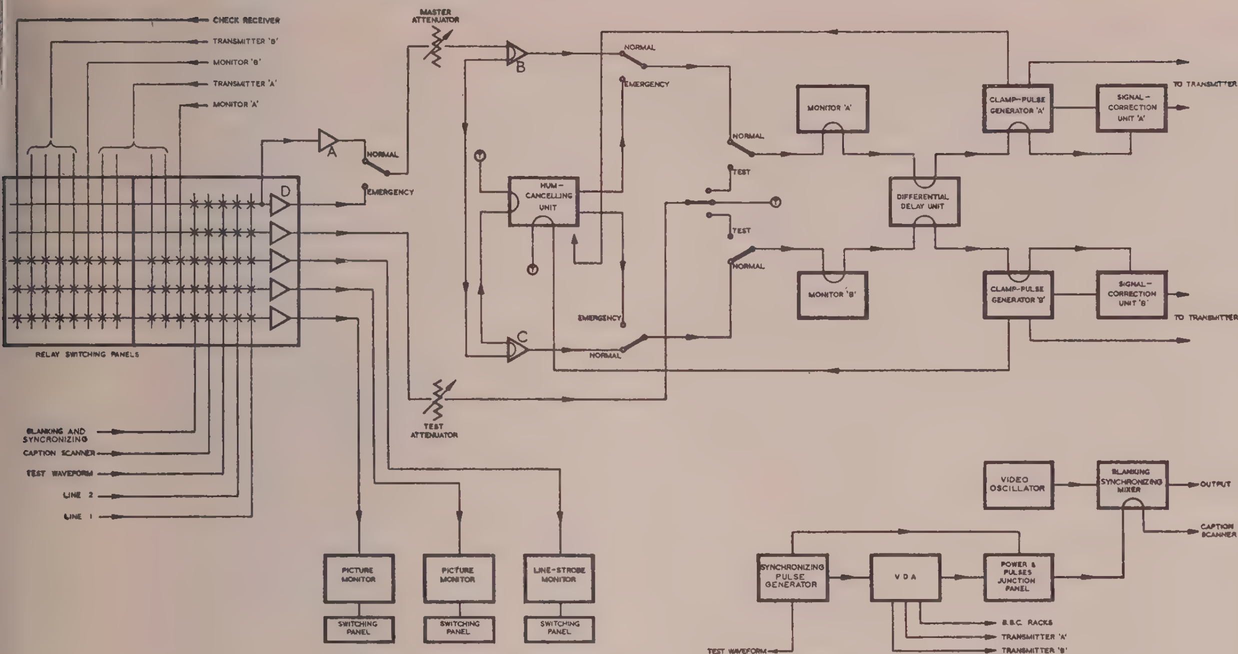

Fig. 1c.—Schematic of control room (vision transmitter).

avour rectifiers of the xenon type which have the high-efficiency haracteristics of the mercury-vapour rectifier and the superior tarting-up features of metal rectifiers.

Switching, control and protection equipment has undergone ttle basic change, although some attempt has been made to mplify this part of the equipment. It is significant in the rogress of electronic engineering that the incidence of fault is ow predominantly in the control and switching systems, where is more difficult to anticipate failure by replacement.

(2) THE CONTROL ROOM

Fig. 1 includes a block schematic of the vision and sound ansmitters and the signal-input switching and all test and onitoring equipment as used by the BBC. It will be seen that ach transmitter receives its input vision signal from a series of nits mounted in the control room.

(2.1) R.F. Drive and Phasing

Experience in paralleling sound-broadcast transmitters[12] operating in l.f., m.f. and h.f. bands has shown that, so long as a common drive is used and some method of phase correction is available, satisfactory performance is obtained. Distortion, noise, linearity, etc., appear always to be roughly a mean of the figures for the individual transmitters. Tests on a pair of Band I vision transmitters showed precisely the same trend, but it was evident that differential video phase control was also required.

The r.f. drive and phasing apparatus for both sound and vision transmitters is contained in cabinets of standard 19 in rack centres, 7 ft high. In these are mounted the vision and sound drives, the phasing amplifiers, power supplies and fault indication panels. Each unit is duplicated, and available for immediate switching. The relation of these units to the whole equipment is shown in Fig. 1A.

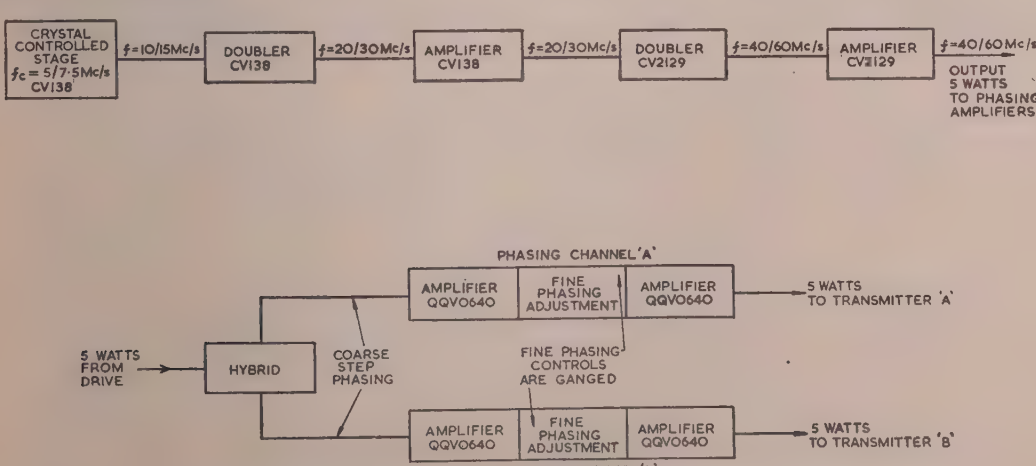

Fig. 2.—Schematic of vision and sound drives and phasing amplifier.

Both sound and vision drives are identical except for frequency (Fig. 2).

Phase indication is provided by comparing pick-up from three points in the feeder system. Three voltage vectors of equal amplitude are derived, one at 0°, one at 180° and a third at nominally 90°. The anti-phase pair are from one transmitter output feeder and the quadrature vector is from the other transmitter output feeder. The deviation from the nominal 90° of the quadrature vector is a measure of the phase difference between the output signals and is obtained by arithmetical subtraction of the resultants of vector additions of the 0° + 90° vectors and the 180° + 90° vectors. Adjustment of the fine phasing control to produce zero indicates the co-phasing of the transmitter output signals. A centre-zero meter gives the phase, in correct sense, of the output of transmitter A relative to that of transmitter B.

Phase difference can be measured up to 50° maximum, and adjustment is provided to give co-phasing with an accuracy of better than 1°. This is found to be a relatively stable adjustment requiring very occasional attention.

(2.2) Vision Input Equipment

The control room contains all the apparatus necessary to provide a hum-free distortion-corrected signal, and clamp pulses for the transmitter video-frequency circuits, so that the transmitter itself contains only straightforward amplifiers and limiters. Controls for setting the clamp and feedback levels are brought from the transmitter to the control desk. Two lines (one spare) from the studio are brought to a set of programme selector switches on the control desk. Three additional inputs are available for the caption scanner, the test waveforms and a spar
(See Fig. 1c.)

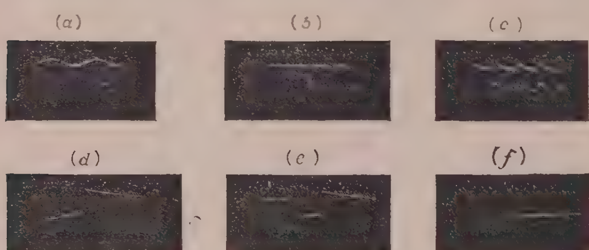

Fig. 3.—Television waveform distortion, 405-line system.

(a) Frame distortion due to 20% 50 c/s modulation of peak-white picture.
(b) Undistorted frame of horizontal black-bar picture.
(c) Distortion of (b) due to *CR* coupling with time-constant of 2·4 millisec.
(d) Trace (c) expanded to show black-level distortion.
(e) Trace (c) expanded to show frame-suppression-period distortion.
(f) Trace (e) expanded.

For an emergency, each transmitter has its own input units an clamp-pulse generator fed from different power sources. I addition, a 'normal-emergency' button on the control des re-routes the signal from amplifiers A, B and C and passe it via amplifier D to the hum-cancelling and l.f.-correctio amplifier. This unit corrects any errors in the incoming signa so that 'emergency' can also cover deterioration of the inpu signal. The unit gives twin outputs as required above.

All video switching is performed by means of relays, the cross talk between lines being better than −50 dB.

(2.2.1) Distortion of Input Signals.

According to the BBC specification, input signals may hav 20% superimposed hum, be differentiated by a time-constant o 2·4 millisec (16 μF and 150 ohms) and have superimposed inter ference pulses up to 1·5 microsec wide equal in amplitude to th synchronizing pulses. The form of this distortion can b appreciated by reference to Fig. 3.

(2.2.2) Hum Cancellation and L.F. Correction.

The transmitter incorporates a system of hum cancellation an l.f. correction[7] designed to remove the forms of undesirabl modulation referred to above. The distortion is removed b detecting the black-level error, filtering and smoothing th

Table 1

Input frequency	Cancellation ratio
c/s	
20	80 : 1
50	300 : 1
100	60 : 1
200	25 : 1
500	6 : 1
800	3 : 1
1 000	2 : 1

resulting step waveform and feeding it back into the vision frequency amplifier in phase opposition, so as to cancel th original distortion. The unit (Fig. 4) is necessary only whe distortion due to hum is of such a level that it requires more tha 30 dB attenuation of 50 c/s hum, which is the maximum that ca be provided by conventional clamp circuits, or when differentia tion of the waveform is excessive.

The unit operates satisfactorily with an input level from +3 d

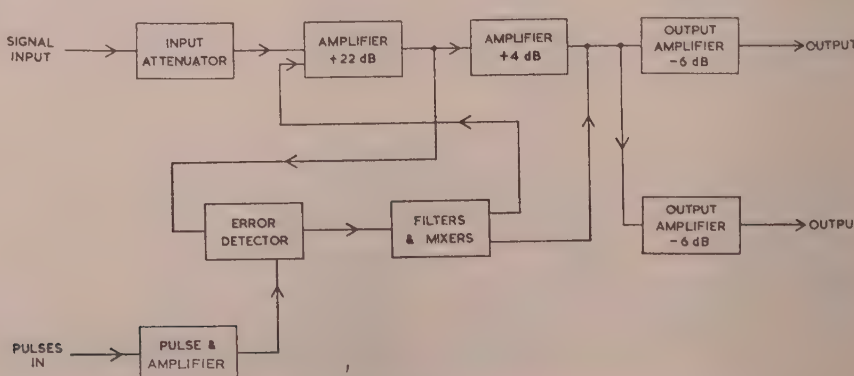

Fig. 4.—Schematic of hum-cancellation and low-frequency correction units.

−18 dB on a standard level of 1 volt d.a.p. in 75 ohms, and ves standard output-signal level. Frequency response is flat ±0·2 dB up to 7 Mc/s.

As designed, the unit will cancel 50 c/s hum of up to eight times e signal amplitude with a 300 : 1 cancellation ratio; this ratio, hich is optimum for 50 c/s components, varies with frequency, shown in Table 1.

.2.3) Signal Correction.

The predistortion necessary to correct for the non-linearity of e r.f. grid-modulated amplifier is accomplished in the signal-orrecting unit, which can provide synchronizing-pulse stretching nd 'white' stretching. To maintain accurate onset of the rious stretching operations, so that the overall linearity is aintained irrespective of picture content, all stages performing e correcting operations are black-level clamped, clamping gnals being derived from the clamp-pulse generator unit. To btain adequate linearity correction towards 'white', three ariables are usually necessary, namely the magnitude, the onset nd the law of 'stretch'.

The stretching operation is obtained in a parallel amplifier hich operates in the non-linear region of its characteristics owards cut off.

The law of the correcting-signal output is adjusted by alteration f the linearizing feedback applied to this amplifier. The onset adjusted by variation of the reference voltage to which the alve is clamped, and the magnitude of stretch is adjusted by arying the relative gain of the parallel paths.

.2.4) Clamp-Pulse Generation.

For normal service the clamp-pulse generator (Fig. 5) will eceive input from the vision-signal source, and may therefore eceive a distorted signal within the tolerances specified (see ection 2.2.1). Even under emergency conditions, when the um-cancellation and l.f.-correction unit is in circuit, the input ignal to the clamp-pulse generator may still contain noise pulses, nd has therefore been designed with full noise immunity and ith as much protection as possible against waveform distortion.

The clamp pulses are derived from a multi-vibrator, triggered by the lagging edge of the synchronizing pulses.

Curve A of Fig. 5 is the input waveform, showing random positive-going noise impulses. Curves B and C show the separated synchronizing pulses with the positive-going impulses removed by the delay-line method. Curve D is the waveform after differentiation; the time-constant of the leading edge (C_2, R_2) is about 10 microsec and that of the lagging edge (C_2, R_2 and R_3 in parallel) about 3 microsec. This circuit discriminates between synchronizing pulses and impulses of much shorter duration. Curve F shows the trigger pulses from V4, the pulse-amplitude discriminator. C_3, R_4 (time-constant = 0·5 microsec) integrates the trigger pulses to give a self-adjusting threshold bias to V4. C_4, R_5 have a short time-constant limiting the charge per pulse reaching C_3, as otherwise V4 would discriminate between frame and line pulses. V5 and V6 are the pulse-forming multi-vibrator.

The pulse period is largely determined by the pulse amplitude at the anode of V5 and by C_6R_7. MR3 limits this pulse amplitude, and as a result the pulse width—nominally 2 microsec—is stabilized to better than ±5%.

The maximum delay of the clamp pulse relative to the lagging edge of the synchronizing pulse is 1·6 microsec for the delay line, plus the maximum width of a noise pulse—say 1·5 microsec—plus incidental circuit delays of 0·3 microsec. With a clamp-pulse width of 2 microsec this means that the lagging edge of the clamp pulse is 5·4 microsec after the lagging edge of the synchronizing pulse. The minimum porch width of 5·6 microsec ensures that no false clamping can exist under limiting conditions.

(2.2.5) Control Console.

Apart from normal operational switching, a considerable amount of test monitoring facilities is provided at the control console. Either of two 14 in picture monitors and a line-strobe waveform monitor can be switched to any of four inputs, four transmitter monitoring circuits or to a check receiver. One of the transmitter monitoring points can be switched locally through a monitoring amplifier to many test points in the vision-

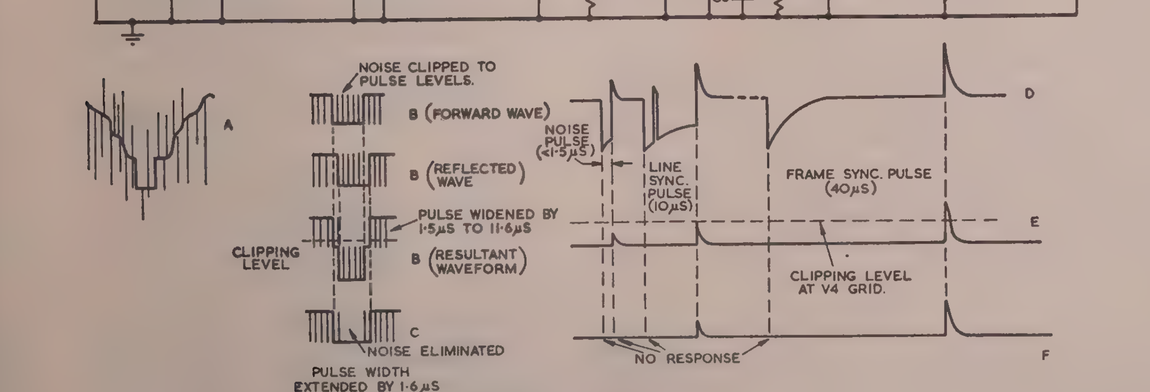

Fig. 5.—Clamp-pulse generator.

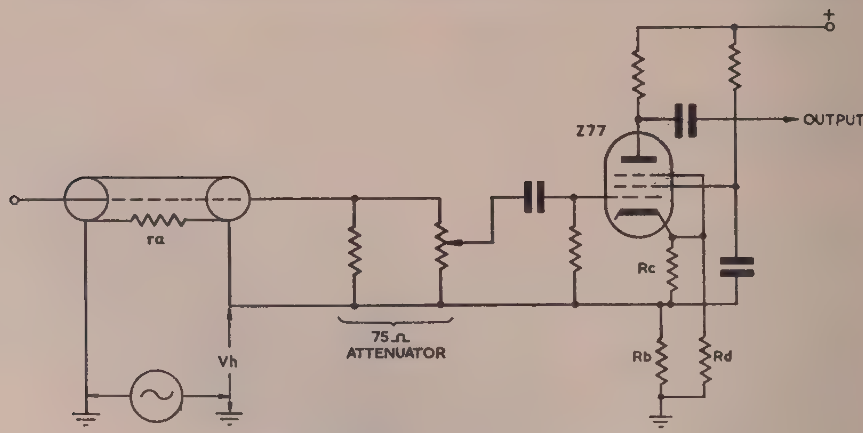

Fig. 6.—Modulation input valve circuit.

frequency chain and can likewise be used for local monitoring on a mobile monitor. Switching operations available in the event of fault to maintain service on one transmitter are provided; these are apparent in Fig. 1c.

(3) THE VISION TRANSMITTER

(3.1) The Modulator

(3.1.1) **Input Stages.**

Hum voltage between earthing points is liable to exist between the control room and the transmitter, and thus incoming signals will probably have superimposed hum, even if the signals have passed through the hum-correction unit in the control room.

A simple hum-cancelling arrangement has been built into the input stage of the modulator with negligible complication (see Fig. 6). By connecting the outer of the coaxial feeder to the transmitter earth through a resistance R_b which is much larger than the series resistance of the feeder, the major part of the hum voltage due to the different earth systems will appear across it. This unwanted hum voltage therefore appears between cathode and earth, while the signal voltage with greatly attenuated hum will appear between grid and cathode. The screen and suppressor are connected to follow the cathode, so that only a very small hum voltage appears at the anode.

The resistor R_d is introduced to act in conjunction with the bias resistor R_c to provide cancellation of the residual hum in the output. Over a selection of 12 valves and without adjustment of any of the circuit component values, hum rejection exceeding 60 dB was obtained, while optimum adjustment gave more than 80 dB.

(3.1.2) **Final Clamp and Black-Level Feedback.**

The input signal to the d.c.-coupled final amplifier and cathode-follower is clamped to ensure a constant radiated black level. The synchronizing-pulse amplitude at the modulator output is more than sufficient to drive the transmitter to cut-off. Stable black level therefore also ensures stable synchronizing-pulse amplitude in the radiated signal.

However, some l.f. distortion, hum and long-term drift in black level may occur subsequent to clamping, and a black-level feedback system[8] is incorporated to minimize these effects (Fig. 7A).

The transmitter output signal is rectified (waveform A). Since the transmitter is cut off during synchronizing pulses, any variation of black level corresponds to a proportional variation in synchronizing-pulse amplitude. This signal is clamped by clamp II (waveform B), the error in black level being transferred

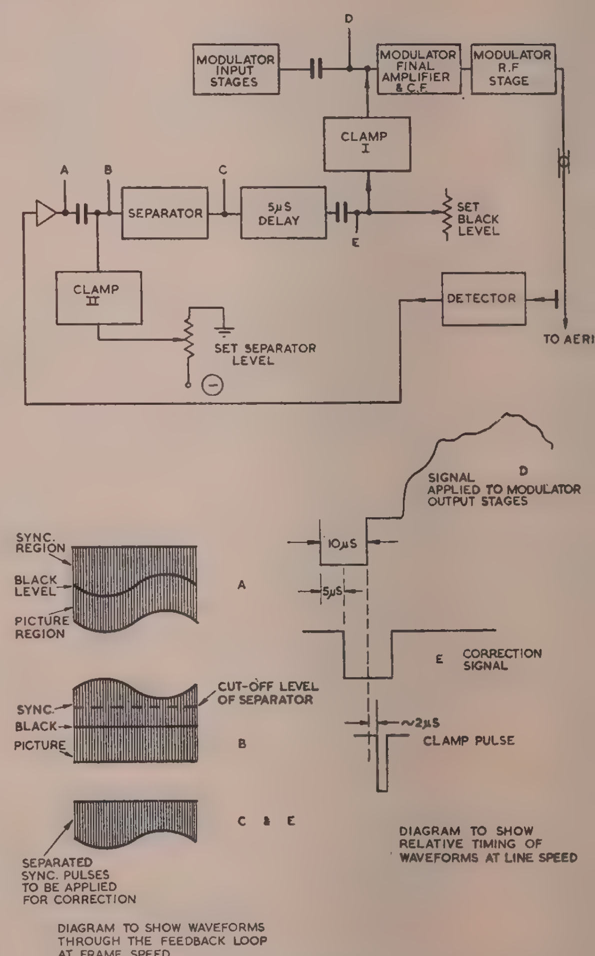

Fig. 7A.—Clamp and black-level feedback system.

to synchronizing level. The picture signals and part of the sy chronizing pulses are removed by the separator (waveform C The inverted and separated pulses are delayed by 5 microsec a used as a correction voltage for the main clamp reference, ea correction pulse being coincident with a clamping pulse.

The level to which 'black' is clamped is thus jointly determined y the 'set black level' control on the desk and the correction-ulse amplitude. This technique has avoided the necessity to se a d.c.-coupled feedback loop common to earlier systems. This system will attenuate error signals at frequencies up to about ne-fifth of the clamping-pulse recurrence frequency.

At the instant of clamping, a fraction of the correction-signal mplitude will be added to the signal. If this fraction is k and he loop gain is A, the criterion for stability can be shown to be

$$k \leqslant \frac{2}{1 + A}$$

In the limiting condition black-level transients will produce a rain of damped oscillations alternatively positive and negative or successive lines. For this train to decay to, say, 1% in ten ines, k must be reduced by a further 17%. In practice, k is djusted to be 70% of the limiting value. For the case in point, $A \simeq 10$ and $k = 0{\cdot}13$.

To mimimize the effect of the relatively large time-constant of he clamp which is determined by the above conditions, a modified ype of clamp bridge has been introduced (Fig. 7B). This gives

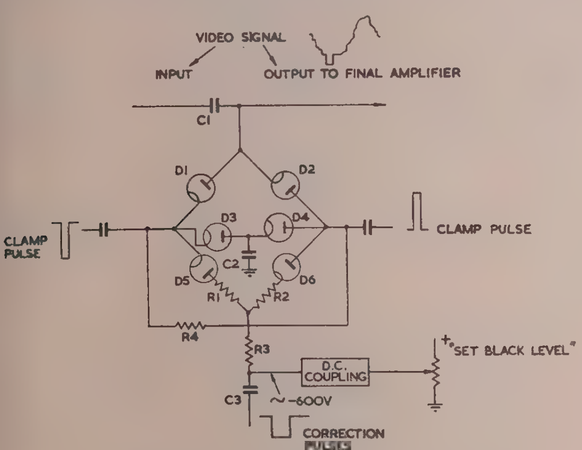

Fig. 7B.—Detail of main clamp circuit.

apid action on errors occurring before the clamped capacitor C1 nd a slower action on feedback correction. The diodes D1–D4 re part of a conventional system of short operating time-onstant (0·4 microsec), the diodes being operated at high current luring the clamping period to reduce the impedance as far as ossible. C_2 is approximately $10C_1$. The diodes D5 and D6 lso conduct during the clamping period, but at a much lower urrent. Correction is applied via these diodes at a time-constant letermined by R1, R2, R3, C1 and C2, and this is adjusted for table operation.

The feedback reduces black-level deviation by 18–20 dB on a ong-term basis.

3.1.3) Final Amplifier and Cathode-Follower.

The availability of 10 kW tetrodes (CR192) suitable for grid nodulation has made possible high-level modulation with a arallel arrangement of naturally cooled 25-watt tetrodes. The se of tetrodes in shunt-regulated amplifiers and cathode-ollowers confers several advantages, owing to their high ratio of lynamic impedance to d.c. resistance. Constant-current opera-ion can be approached, for example, in the shunt-regulated athode-followers without the necessity for the regulator valve o handle the bulk of the reactive current demand, as is the most economic case when using triodes. Equal reactive-current handling by each valve of the shunt-regulated amplifier or cathode-follower is more easily obtained, and this results in greater conversion efficiency. With the screen-to-cathode voltage constant, greater anode-voltage swings are possible with a lower minimum anode voltage than is possible with comparable triodes. This has resulted in the possibility of being able to earth the h.t. positive line and in the saving of a stabilizer system. Fig. 11 shows that the peak demand of current due to modulated-stage grid current is supplied equally by both valves of the shunt-regulated pair, with only half the current demand on the shunt stabilizer system. This represents an improvement over earlier systems in which the tendency was towards making the shunt stabilizer an absorber-type circuit, resulting in a constant load equal in magnitude to the peak-loading condition.

The reduction of Miller capacitance has also confirmed advantages in the signal circuits. The price paid for these advantages is the necessity to provide stable screen supplies and negative feedback in the shunt-regulated-amplifier section, in order to recover the bandwidth lost in raising the dynamic load impedance. The d.c.-connected feedback network is a complication, but it has provided a further degree of gain stability and linearity in addition to recovering the bandwidth, and has resulted in a higher overall conversion efficiency for a given performance.

The use of a cathode-coupled pair, V1 and V2, provides a useful high-impedance injection point for the feedback voltage, a high-impedance input to the amplifier and a significant degree of isolation from any residual hum on the —800-volt h.t. line.

The single pair of valves, V2 and V3, cannot handle the peak reactive-current demand of the output stage and the inevitable circuit capacitances, so an additional regulator valve, V4, is included. On peak demands at the higher vision frequencies the a.c.-coupled regulator V4 contributes equally with V2 and V3 to the load demand.

The shunt-regulated output stage V6 and V7 consists of five pairs of KT67 valves in parallel and can provide a peak reactive current of 0·55 amp for a mean h.t. current of 0·275 amp.

The path of the modulated r.f.-amplifier grid current is indicated by the arrows in the diagram, the only d.c. earth in the grid-current circuit being at the grid-current meter. The grid-current demand is shared equally by V6 and V7, one half flowing via V6 and V8 and the other via the shunt stabilizer, V7 and V8. Equal sharing is achieved by correct design of R_2. The output impedance of the stage for this condition of operation is about 8 ohms.

The load on the modulator consists of 350 $\mu\mu$F external and a further 150 $\mu\mu$F due to the modulator output stage—a total of 500 $\mu\mu$F. The voltage excursion from black to white is about 190 volts. A reasonably shaped transient response of 0·13 microsec from black to white therefore requires reactive current of about 0·5 amp, in addition to the 250 mA transmitter-grid current.

The d.c. levels at the output terminals of the modulator are: peak white, —120 volts; black level (pedestal), —310 volts; synchronizing-pulse bottom, from —450 to —475 volts.

Peak-white limiting is provided in the final amplifier–cathode-follower coupling network by a valve driven from the output terminal, the time-constant of the limiting action being designed to give complete recovery of level during the synchronizing-pulse period and minimum deterioration of the picture during limiting.

(3.2) The R.F. Section

The connection between the penultimate r.f. amplifier and the grid-modulated amplifier calls for special consideration. The problems associated with this part of the circuit have already been commented upon and discussed.[2,3,9] The main problem that arises is due to the flow of grid current in the grid-modulated

amplifier. In order to prevent non-linear regulation it is necessary to make the driving impedance very low compared with the peak loading due to peak grid current. Moreover, since the onset of grid current may take the form of a transient of very small rise time, the low driving impedance must either remain negligibly low over the video-frequency band or be aperiodic.

The problem has been solved in a number of ways. The most obvious and the least economical is to load the driving stage until the grid load represents only a small part of the total load. As adopted in early television transmitters,[1] this procedure also provides an aperiodic source impedance. In a post-war design of transmitter,[2] a hard-driven driver stage was used to produce a low impedance which the designers claimed was adequate, while in a still later design a cathode-follower driving stage was used to produce an aperiodic effective driving impedance of about 10 ohms.[3]

A clearer picture of both the problem and possible solutions can be obtained by drawing an analogy between this problem and a familiar video-frequency problem, namely that of providing a constant h.t. supply over the video-frequency band despite substantial changes of current—a problem usually solved by the use of constant-impedance networks or voltage stabilizers.

Suppose that the driving stage of the grid-modulated amplifier is a high-efficiency class-C amplifier with narrow bandwidth. If its output impedance could be made sufficiently low, and if a direct connection to the modulated valve could be made, this would form a reasonable practical solution, since if the output impedance of the driver restricted non-linearity to, say, 5%, the change of excitation voltage driving the grid-modulated stage over the range of modulating frequencies will be limited to 5%. In practice, this is not possible and the usual driving stage is coupled by a transformer to the output stage, in order to achieve a sufficiently low impedance; the coupled circuit or its equivalent is normally made of sufficient bandwidth. If the bandwidth of this stage is intentionally so limited that the maximum conversion efficiency is obtained, the driving-stage impedance will be aperiodic only over a limited band of frequencies; and if components of load current are demanded from it at frequencies outside its bandwidth, distortion due to the well-known ringing phenomena will occur.

When such a high-efficiency circuit exists or can be designed and it is necessary to drive a grid-modulated stage from it, we must—by analogy—first determine over what small band of frequencies the circuit may be regarded as a substantially constant resistance.

This is a direct analogy of the power supply which acts as a resistance source up to the frequency at which the smoothing components cause a significant change of impedance. In the low-pass circuit we extend the constant resistance over a larger frequency band by adding sections, and can proceed in exactly the same way in the band-pass case. In all cases, of course, $R = \sqrt{(L/C)}$, and in the band-pass case each tuned circuit is tuned to carrier frequency.

In practice, the application of this principle is not always simple. With modern valves of the type used in this transmitter the maximum power output is obtained at a considerable bandwidth. The physical complication of applying constant-impedance drive systems is also such that a compromise is often the better practical solution. In the Crystal Palace transmitters a small amount of damping with the simplest possible transfer connection was all that was necessary to meet the required performance. For full exploitation of valves, however, it would seem that the constant-impedance drive will in many cases offer a substantial improvement. This may be the case with Band III and Band IV transmitters, where the additional circuit elements can conveniently be made as line sections.

As is well known, the output obtainable from a given pair c push-pull valves working under class-B conditions is given by

$$P = \frac{KI^2}{16\pi C\Delta f}$$

where P = Power, watts.
I = Peak available emission current per valve, amp.
K = Circuit factor (1 for single-circuit, $\sqrt{2}$ for double circuit and 1·5 for triple-circuit coupling).
C = Total circuit capacitance, μF.
Δf = Bandwidth between 3 dB points, Mc/s.

With this amplifier stage (which has a total circuit capacitanc of 23 $\mu\mu$F using CR192 valves) and a peak power output o say, 18 kW, the power-capacitance product is 23 × 18 kW-$\mu\mu$ and is constant for a given bandwidth and emission; thus saving of 1 $\mu\mu$F in the circuit capacitance will increase th power output by about 800 watts. The problem of minimizin spurious circuit capacitance by careful design reconsideratio becomes important.

With this transmitter the output circuit is triple tuned. Fc maximally flat response the input and output sections of th 'triple' are rigidly related, while the intermediate circuit can hav any convenient LC ratio. The flexibility in the possible desig parameters of the intermediate circuit provides an excellent ai to physical realization of the theoretical maximally-flat-respons condition or any other condition chosen. For maximally-fla and Chebyshev response the circuit relations are shown in Fig. 8

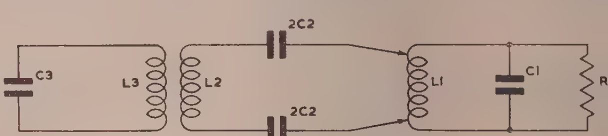

Fig. 8.—Realization of output circuit.

(a) Maximally flat: 55 Mc/s, 3 dB, f_c = 44 Mc/s

R_1 = 51·5 Ω	C_1 = 280 $\mu\mu$F	L_1 = 0·047 μH
K_{12} = 0·153	C_2 = 17·5 $\mu\mu$F	L_2 = 0·75 μH
K_{23} = 0·088	C_3 = 23 $\mu\mu$F	L_3 = 0·5 μH

Q-factor of primary circuit = 12.
Q-factor of output circuit = 4.

(b) Triple peaked: V_p/V_v = 1·02.

R_1 = 51·5 Ω	C_1 = 420 $\mu\mu$F	L_1 = 0·31 μH
K_{12} = 0·116	C_2 = 17·5 $\mu\mu$F	L_2 = 0·75 μH
K_{23} = 0·082	C_3 = 23 $\mu\mu$F	L_3 = 0·57 μH

Q-factor of primary circuit = 12.
Q-factor of output circuit = 6.

Obviously a small migration of values from the maximally-flat t the peak response condition is permissible, if necessary, withou significant sacrifice of transient response.

The problem of handling both vision-frequency and radic frequency currents in grid-modulated amplifiers entails carefu design of all the current paths. To preserve the effective band width of the modulated circuits the supply impedances must b aperiodic, and all connections, including earth returns, must b included in this consideration of aperiodicity. The screen-gri supply is stabilized at its source, and the cathode impedance i kept to a minimum to minimize r.f. degeneration.

On the modulation input circuit of the grid-modulated stag further precautions are necessary.

Assume a perfect modulator output impedance of R ohm from which is derived a perfect vision-frequency signal; it is the necessary to apply this signal between the grid and cathode of th modulated stage.

The capacitance of the grid-to-cathode circuit shunted by th non-linear-resistance component due to grid current represent the unavoidable load on the modulator. The connection between the modulator and modulated stage, and the chokes c

milar impedances used to enable the vision-frequency signal to perate in parallel on the modulated-stage grids without disrbing the push-pull r.f. driving conditions, present a series npedance which is predominantly inductive. Series inductance uses the voltage across the capacitance to rise with increasing equency and increases the apparent capacitance loading on the urce, thereby demanding more reactive current. Generally speaking, the use of $\lambda/4$ lines as chokes tends to help in some cases, but whatever the form of the connection, either the capacitance loading and the voltage across the capacitance load increases rapidly or, if the characteristic impedance of the lines is low, the rise is less rapid but the capacitance load on the modulator is heavier over a greater frequency band.

Fig. 9 illustrate these effects and shows that a satisfactory

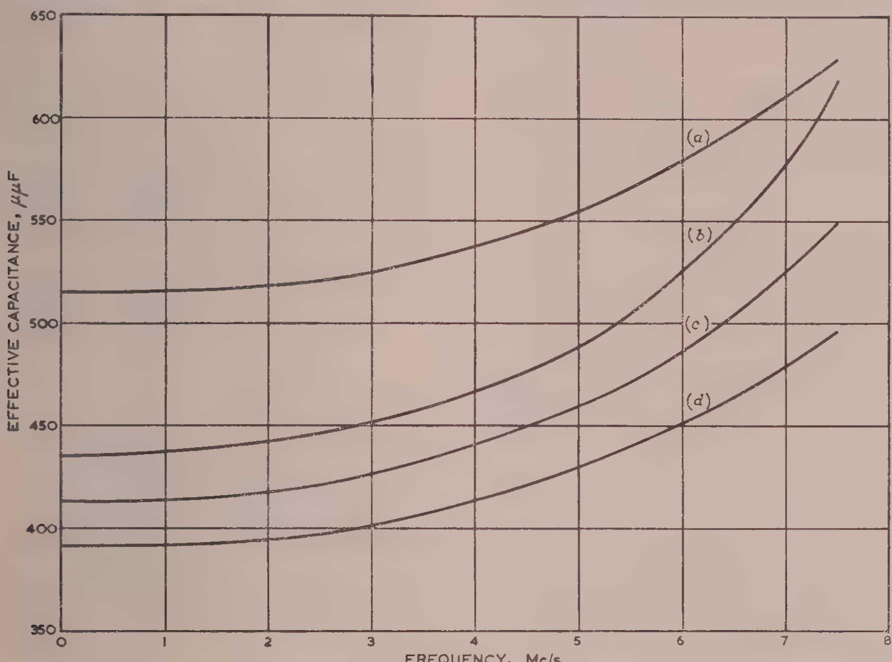

Fig. 9A.—Effect of using lines as impedances.

(a) $\lambda/4$; $Z_0 = 30\,\Omega$; $f_r = 16$ Mc/s.
(b) $\lambda/4$; $Z_0 = 60\,\Omega$; $f_r = 13$ Mc/s.
(c) $3\lambda/16$; $Z_0 = 60\,\Omega$; $f_r = 14$ Mc/s.
(d) $\lambda/8$; $Z_0 = 60\,\Omega$; $f_r = 17$ Mc/s.

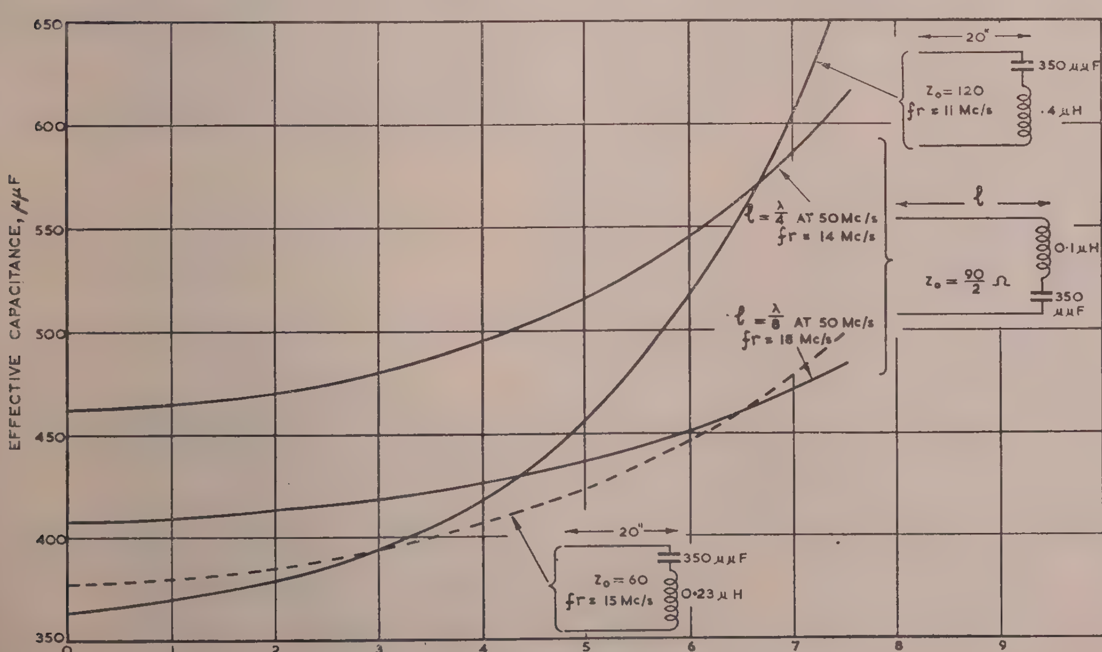

Fig. 9B.—Relative performance plotted against inductive loading.

compromise is possible at the expense of some modulator volt-ampere output.

(3.2.1) Description of the Vision Transmitter.

The vision transmitter (Fig. 1B) uses push-pull circuits with lumped circuit elements, which reduces costs, enhances reliability and gives a general appearance which engenders confidence in the minds of the operational staff.

Input from the external driving source is at 5 watts into 75 ohms and at radiated frequency.

The first stage is a push-pull-connected double-tetrode of type QQV0640, the tuned-grid circuit being inductively coupled to the feeder and the tuned-anode circuit capacitively coupled to the grids of the penultimate stage. H.T. and screen supplies to this stage are non-stabilized and are from a common supply unit. The filament heating is by alternating current.

The penultimate amplifier uses four type QY4–250 valves in push-pull-connected parallel pairs. This stage is situated immediately over the first stage, to enable short input connections to be used. These valves are self-neutralized at about 60–65 Mc/s; cross-over-capacitance neutralizing is necessary below this frequency, and parallel-capacitance neutralizing above it. The use of valves in parallel at very high frequencies is not considered ideal technically, but bearing in mind the economics of the problem, this solution proved satisfactory.

The penultimate stage uses an anode inductor comprising two vertical rods with a short-circuiting strap to give a preset inductance.

The grid of the final amplifier stage is coupled via a capacitive potentiometer to the penultimate-stage anode circuit. Damping is provided across this circuit, the overall damping impedance being about 600 ohms. Two peak rectifiers are provided to monitor the peak modulation-voltage excursion, i.e. in the positive and negative sense. This is a valuable aid in setting up the bias and driving voltages on the final amplifier. The anode circuit is triple tuned and consists of a primary inductance, of the clamped-up bar type, across the anodes of the pair of type CR192 tetrodes in push-pull, and is tuned by a screw-driven capacitor plate. A secondary balanced tuned circuit is inductively coupled to the primary inductance and directly tapped across the output circuit. This circuit converts from balanced to unbalanced 51·5-ohm output.

The filaments, which are d.c. heated, are fed via $\lambda/4$ lengths of Pyrotenax cable. The screen supply is built out to 100 ohms and the anode supply to 150 ohms by the conventional constant-impedance-network technique.

A switch in the grid circuit enables the modulation to be removed and replaced by a controllable bias supply, to permit the final stage to be set up to simulate any required modulation level.

In the power-conversion stages no hot-cathode mercury-vapour valves were permitted. In the intermediate power-level stages xenon valves are used, while the final h.t. supply is from selenium rectifiers mounted on trucks and housed in the air stream.

The control circuits are completely sequenced and interlocked, so that the transmitter can be brought on power by pushbuttons either at the transmitter or from the control desk.

Complete overload protection is provided, and indicator lamps on the front of the transmitter indicate location of fault.

Built into the front of the transmitter is the r.f. envelope monitor, giving a cathode-ray-oscillograph display which enables modulation levels to be set up correctly. Radio frequency picked up from the feeder is directly displayed without the use of intervening valves or circuits, except a double-tuned circuit of 8 Mc/s bandwidth at the 3 dB points. The time-base permits display at either half line speed or half frame speed. The monitor has its built-in power supplies and is a self-containe removable unit.

(3.2.2) Summary of Operating Conditions.

Operating conditions for the penultimate stage are as follow

Valves	Four type QY4–250.
Power output (total)	700 watts.
H.T. voltage	2·95 kV.
Anode current	115 mA per valve
Power input	340 watts per valve.
Dissipation	165 watts per valve.
Screen voltage	150 volts.
Screen current	14 mA.
Screen dissipation	2·4 watts.

Operating conditions for the final stage are as follow:

Valves	Two type CR192.
Total circuit capacitance	23 $\mu\mu$F.
Power output	17 kW per pair.
Anode voltage	5·8 kV.
Anode current	2·85 amp per valve.
Anode input	16·5 kW per valve.
Anode dissipation	8 kW per valve.
Screen voltage	1·3 kV.
Screen current	180 mA per valve.
Screen dissipation	234 watts.
Anode efficiency	51·5%.
Valve efficiency	50%.
Grid current	250 mA per pair.

(3.2.3) Adjustment of Triple-Tuned Circuit.

The circuit diagram is shown in Fig. 8.

The coupling between primary and intermediate circuits i inductive and is adjusted by moving L2 relative to L3. Th coupling between intermediate and output circuits is by direc tap on to the output circuit, and is adjusted by varying L2 This was found more convenient than moving the taps on th output circuit.

The output load, R1, is unbalanced, but the arrangement of th output circuit is such as to provide an unbalanced-to-balance transformation. L1 consists of two feeder sections connected t an earth plate, C1 being connected between the free ends. Th load presented to the intermediate circuit is balanced. Setting-u may be performed either by the poles and zeros method[4] or b setting the individual parameters to the design values.[11] Th second method was chosen and is described below.

For the triple-tuned circuit with a maximally-flat response th specified parameters are[10]

$$K_{23} = \frac{\Delta f}{f\sqrt{2}}$$

$$K_{12} = \sqrt{\frac{3}{2}}\,\frac{\Delta f}{f}$$

$$Q_1 = \frac{f}{2\Delta f}$$

where f is the centre frequency and Δf is the bandwidth betwee 3 dB points.

In addition, each circuit must be resonated at the centre fre quency under the following conditions:

(a) Primary tuned with intermediate open-circuited.
(b) Intermediate tuned with both primary and output circui short-circuited.
(c) Output tuned with intermediate open-circuited. Fo $f = 44$ Mc/s and $\Delta f = 5{\cdot}5$ Mc/s, $K_{23} = 0{\cdot}088$, $K_{12} = 0{\cdot}15$ $Q_1 = 4{\cdot}0$ and $C_1 = 280\,\mu\mu$F.

In a double-tuned circuit with infinite Q-factor the fractiona bandwidth between primary response peaks is equal to the coeff cient of coupling. For finite Q-factors the error can be deter

ned, but for values normally found in transmitter circuits the ror can be neglected, which simplifies the measurement. stead of using a variable-frequency oscillator and a separate tector, it has been found that a grid-dip oscillator can be used th to tune each circuit to the centre frequency and to determine e frequencies of the two peaks. In effect, the grid-dip oscillator ts both as the variable-frequency source and the detector.

The circuits are taken in pairs, i.e. primary and intermediate, en intermediate and output, and the coupling factors set as scribed below.

The primary circuit is correctly tuned when tuning the inter-ediate has no effect on the output at centre frequency. With e primary circuit thus tuned the output circuit is in tune when aximum output is obtained. With both primary and output rcuits tuned, the intermediate circuit is tuned to give a sym-etrical response. Residual errors are eliminated by adjust-ents as indicated by the theoretical error curves.[3]

2.4) Summary of Overall Performance of Transmitter Vision-Frequency Channel.

coming Signal.

Nominal amplitude	1 volt d.a.p.
Nominal picture synchronizing-pulse ratio	70 : 30
Picture-signal amplitude tolerance	±3 dB.
Synchronizing-pulse amplitude tolerance	+6–10 dB.
Noise-pulse width	1·5 microsec (max).
Noise-pulse amplitude	±1 volt d.a.p.
stortion	The signal may be differentiated at a time-constant not less than 2·4 millisec.
um	The incoming 50 c/s hum may rise to a value equal in amplitude to the signal.

equency Response.

gnal at low level	
Over the vision-input circuits and the modulator	0·5 dB at 5 Mc/s.
Overall	0·3 dB at 3 Mc/s.
gnal at full amplitude	
Overall	0·3 dB at 3 Mc/s.

Rise Time.

Test input signal rise-time, 0·1 microsec, sine-squared transition positive and negative going, full or part amplitude.

Output at the modulator	0·14 microsec.
Overall	0·15 microsec.

Black-Level Stability.

Better than 2% over an indefinite period.

Radiated Hum.

Expressed as a ratio of d.a.p. hum voltage to d.a.p. vision-signal voltage.

At 50 c/s	Better than 50 dB (where signal contains maximum hum).
At 300 c/s	Better than 52 dB.

(4) THE SOUND TRANSMITTER

Designed for a radiated carrier power of $4\frac{1}{4}$ kW, the sound transmitter is 15 ft long, 3 ft 9 in deep and 7 ft high.

The r.f. unit consists of three stages: input from the driving source is at 5 watts at radiated frequency; a double-tetrode (type QQV0640) in push-pull, supplies 40 watts to drive the penultimate amplifier, which uses two valves, also (type QY4–250) in push-pull, and supplies 700 watts to the modulated amplifier. Neutralizing is achieved by a variable capacitor connected between the screens of the pair of valves. The final stage, to which anode modulation is applied, uses a pair of type BR191 valves in push-pull, earthed-cathode connected with conventional bridge neutralizing. The 51·5-ohm output feeder is inductively coupled to this stage by a simple double-tuned coupled circuit.

Overload protection is by cathode-current relays and comparators using both rectified r.f. and modulation voltages from pick-up probes in the outgoing feeder.

The modulator is push-pull connected throughout and employs two stages of cathode-follower prior to the main modulator. Two stages of internal feedback are employed, and the arrangement of the stages and the feedback loops are shown in Fig. 10. Limiting diodes are also incorporated, but are not shown on the diagram.

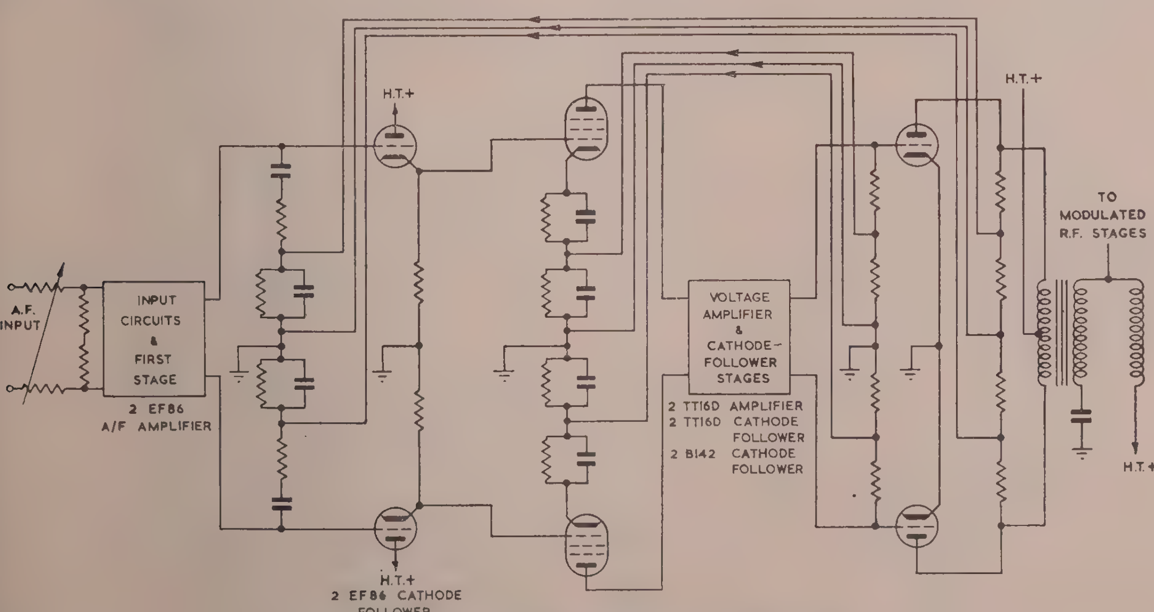

Fig. 10.—Sound modulator, showing feedback arrangements.

A built-in monitor, with cathode-ray-oscillograph indication, enables both a.f. waveforms and r.f. envelope waveforms to be displayed; this facilitates the correct setting-up of all circuits. The sound transmitter gives distortion of less than 1% from 30–40% modulation, less than 1·5% up to 70% modulation and less than 3% up to 90% modulation over the frequency band 30–10 000 c/s. Input power is 14 kW at carrier frequency and 18·5 kW at 90% modulation.

Higher-power conversion rectifiers are of the xenon type. The transmitter is completely interlocked for sequence starting by pushbuttons at the transmitter and at the control desk.

Overload protection and indication lamps to show the position of faults are provided.

(5) OPERATIONAL RELIABILITY OF THE VISION SYSTEM

(5.1) Breakdown

The principle underlying the design has been to provide parallel paths wherever possible, so that in the event of breakdown the faulty path can be shut down and operation allowed to continue with the other. Where a common path is essential in the early part of the input equipment the 'normal-emergency' relays bring into use an alternative path complete with its own supplies. In addition, patching jacks are provided to permit the by-passing of relays which might develop faults.

The principle has also been followed of concentrating as much of the more complex equipment as possible in the control room, where it is accessible without breaking interlocks. In the black-level feedback system, where this principle cannot be followed, provision has been made to open the feedback loop and operate on simple d.c. restoration or simple clamping.

In the event of breakdown the operator's first duty is to press the 'emergency' button. If normal service is restored the fault must lie in the input equipment; if not, then in all probability one of the transmitters is at fault, and a quick check with the monitoring facilities provided will reveal which one. The operator can then shut it down from the console and continue normal programme at reduced level with the other. He can switch the faulty transmitter to test load and apply test signals by way o the independent test channel provided; normal fault locatio procedure can then be carried out. Input-equipment faults ca likewise be located without interrupting the programme.

(5.2) Clamping Stability

The clamp generator will accept pulse noise up to 1·5 microse width and considerable hum and l.f. distortion. However, i pulse noise of greater width or abnormal distortion beyond th specified limits should be present on the incoming signal, mis timing of clamp pulses might result. To maintain service, al clamping must be eliminated. On the modulator this will be don by switching the clamp to d.c. restoration and in the control roon by patching-out the signal-correction system. This will result i reduced power and some attenuation of synchronizing pulses owing to the absence of stretching. Nevertheless, if the picture i important and viewable, it can still be radiated sufficiently well t continue the service.

(6) THE INFLUENCE OF COLOUR TELEVISION ON TRANSMITTER DESIGN

The transmission of colour information in addition to th conventional luminance information imposes additional demand on the transmitting system. If, for example, we consider th American N.T.S.C system, the additional demands are due to

(*a*) The presence of the colour synchronizing burst in the line blanking period.

(*b*) The necessity to maintain the phase of colour signals within few degrees over the complete amplitude range.

The presence of the burst in that part of the waveform normall used for clamping makes conventional 'hard' clamping unsuitable owing to the distortion caused to the transmitted burst. Soften ing the clamp action by series impedance can alleviate thi situation and is acceptable, provided that there are not man such clamps involved; the impedance discontinuity becomin

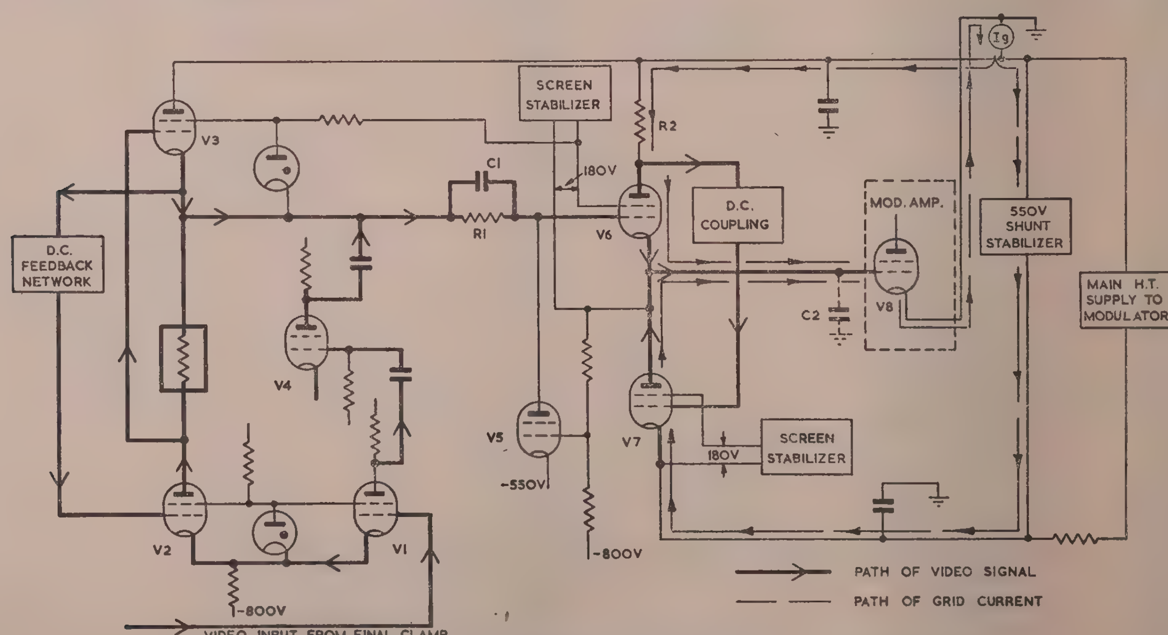

Fig. 11.—Vision-modulator output amplifier and cathode-follower arrangement.

gnificant as the number of clamps is increased above two or ree. Alternative d.c. correcting means have been devised and ll probably gradually displace conventional clamps where there the probability of colour transmission.

The accurate phase/amplitude relation required by the colour-ansmission system demands a degree of amplitude linearity far eater than that required for monochrome television and over greater range of power demand if 100% saturated colours are be transmitted. In the present series of transmitters care has en taken to ensure an adequate power-loading capability under ie class-A conditions of the modulator. Any residual errors the phase/amplitude relation can then be corrected by a pre-stortion method shortly to be published.

For colour transmission the transmitters will have the main amp softened, but not to any great degree, since, with this quirement in mind, the driving-source impedance of the amped stage has been made very low so that the disturbance to e impedance during clamping is almost negligible.

To achieve signal correction, i.e. synchronizing-pulse stretch-g and linearity correction, a unit alternative to that described rlier has been developed and is now available. This uses a stem of d.c. correction without impedance discontinuity in the gnal circuits.

(7) ACKNOWLEDGMENTS

Quite naturally, the work involved in the development and sign of television transmitters is considerable, and their final sign is due to a large number of people. The authors gratefully knowledge the work done by teams under the leadership of essrs. J. Sutton, J. E. Nixon, G. Partington, S. U. Nolan, . Haywood and D. F. Bowers.

Thanks are also due to Mr. J. E. Nixon for assistance in eparation of the paper.

The authors desire to thank the Engineer-in-Chief of Marconi's ireless Telegraph Co., Ltd., for permission to publish the paper.

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DISCUSSION BEFORE THE RADIO AND TELECOMMUNICATION SECTION, 4TH APRIL, 1956

Captain C. F. Booth: This is indeed an historic occasion in spect of television in the United Kingdom; first, we have with members of C.C.I.R. Study Group 11 from many countries, d secondly, the three papers presented this evening mark the ssing of Alexandra Palace, which has given London its television rvice since 1936. It is indeed a tribute to the architects of the 5-line system, to the transmitter and receiver designers and to e British Broadcasting Corporation, that picture quality has proved almost continuously. Since the service was re-opened 1946, great progress has been made; then there were a few ousand receivers, now there are upwards of six million, and e Corporation is providing a service covering over 93% of the pulation. Additionally, during the past few months, the dependent Television Authority has been set up and is providing rapidly expanding service.

It was a bold step to transfer a well-founded service for the etropolitan area from Alexandra Palace to Crystal Palace. The asons are explained in the paper by Messrs. McLean, Thomas d Rowden; ultimately a service will be available to upwards one million additional people. The transfer has presented fficulties, and I should like the authors to indicate them and e precautionary steps taken.

I note from the paper by Messrs. Cooper and Morcom that the rallel technique has been solved in respect of Band I transmit-s. It is an excellent achievement which should not be belittled, t I do wonder why the authors did not finish the job by fitting tomatic phase control. Have they also solved the problem of ralleling Band III transmitters?

Messrs. McLean, Thomas and Rowden state that they gave preliminary consideration to the interleaving of Band I and Band III aerials; I should like to know whether they have continued this work, and, if so, the results thereof.

I was recently privileged to inspect—with people from some 20 countries—the new Crystal Palace station; it is certainly a sound engineering job, and without doubt it will make a contribution to the television service comparable with that of its predecessor.

One final point: reference is made in the papers to the very desirable aim of achieving a design suitable for colour. I merely stress—as one paper says—that an agreement that the vision transmitter should be designed with the requirements of a colour signal of the N.T.S.C. type in mind does not imply that an N.T.S.C. system or, indeed, any colour system would be used. In fact, as is pointed out in the papers, a decision regarding colour standards is some way off.

Mr. C. E. Strong: I am not too sure about the advisability of parallel operation of transmitters in a station like this. No doubt it is effective with high-power broadcasting transmitters, but with rather modest-power transmitters including relatively complex input circuits, it might be another matter.

Parallel operation has, of course, the advantage that you might get a fault and not have even a momentary interruption of the programme. Against this, however, there are two transmitters to be similarly lined up at the same time for equal performance. The number of components in service is approaching double; there is extra complexity, perhaps, in phasing of the video and

radio-frequency circuits; there is a drop of 3 dB if one transmitter is taken out of service for maintenance, and of 6 dB in the condition of the normal fault. This drop of 6 dB may be a little too much at the edge of the service area, and I get the impression that Mr. McLean and his co-authors have indulged in a little special pleading on this point. It might have been better to have two transmitters of the full power, one of them in operation and the other in reserve, with cathodes on partially, ready to be switched over automatically and instantaneously.

The present e.r.p. of the station is 200 kW, but the BBC say they may want to double this. Now, if they had installed two transmitters of full power, one in operation and the other in reserve, they would be able to have double power any time they wished, just by connecting the transmitters in parallel. I admit that nothing would be saved in either case on the antenna system. I agree that it is still a good idea to have the antennae and feeder systems in two groups.

I fully appreciate the main advantage of parallel operation, which is perhaps that there is not even a momentary break in service on a fault. There are also certain incidental advantages, of course, having to do perhaps with the availability of valves, and possibly with avoiding the necessity for elaborate modulators.

Mr. I. F. Macdiarmid: I had the opportunity of carrying out an independent series of waveform measurements on the Broadcasting House–Crystal Palace link in January, 1956, the method of measurement being that currently used by the Post Office for the testing and specification of new links. In this method* a rating factor is obtained from various features of the received waveforms when standard test signals are transmitted.

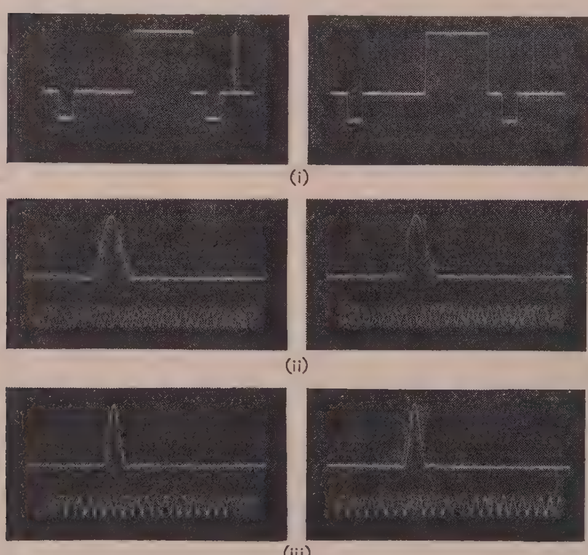

Fig. A.—Test waveforms before and after transmission from Broadcasting House to Crystal Palace.

Left-hand side: Before transmission.
Right-hand side: After transmission.
(i) $2T$ pulse-and-bar waveform.
(ii) $2T$ sine-squared pulse (0·33 microsec).
(iii) T sine-squared pulse (0·17 microsec).

Fig. A shows the transmitted and received waveforms. The principal distortion is the slight lift of the trailing corners of the T and $2T$ pulses which can be seen in the photographs. The measured rating factors, in the nomenclature of the reference, are as follows: $K(\text{bar}) = 0{\cdot}1\%$, $K_1 = 0{\cdot}4\%$, $K_2 = 0{\cdot}4\%$, $K_3 = 0{\cdot}4\%$, $K_4 = 0{\cdot}2\%$. This makes the overall rating factor 0·4%, which adequately meets the 0·5% which I would consider an appropriate design objective for a link of this kind.

The design limits in Section 2 of the paper, difficult as they are to achieve in practice, are still too wide to ensure satisfactory waveform performance. The attenuation and group-delay tolerances permit a rating factor several times greater than 0·5%, while the transient-response limits give little additional information except to restrict the rating factor for the 40 microsec bar to 1%.

The figures quoted for linearity appear to occupy rather a large proportion of the usual limits for a 500-mile chain of links. However, the tests which I carried out showed the variation of both picture and synchronizing-pulse amplitude with picture content to be less than 1%—a more than adequate performance.

Sir Harold Bishop: I am particularly interested in what Messrs. Cooper and Morcom have to say about the design of transmitters, but it is noteworthy that the initial power of the Crystal Palace transmitter is, after all, only twice that of the Alexandra Palace station of 20 years ago. I do not know whether this means that all or nearly all the improvements in performance are to be found in the aerial; but perhaps any such suggestion would be very unfair on Mr. Cooper and his colleagues.

I am rather sorry that Messrs. McLean, Thomas and Rowden disposed of the question of balance between aerial gain and transmitter power so quickly. Why did we decide that eight tiers for the aerial was the best compromise?

In the Introduction to this paper there is a reference to the reliable service which can be provided by 100 μV/m signal. I agree that this is largely true, but it would be of interest to know more about the values adopted by other countries. However, I doubt whether we shall continue to find that 100 μV/m will be adequate for all time; about 250 μV/m is a more reliable signal, although you can always get reasonable fringe-area reception on the lower field-strength.

In Table 1 there is some confusion about the figure of 15·2 million people who are being served down to the 100 μV/m line, because reference is also made to 14·5 million. The authors may be able to explain this, but coverage figures are, in fact, very confusing unless they are carefully specified. Some of the areas, especially the fringe areas, may be covered twice, and the population must not be counted twice.

There is no doubt, however, that the Crystal Palace station will cover about a million and a half more people than did the Alexandra Palace station, mainly because, as is shown on the service area map, we are covering the south coast far more adequately than we have done before. It is obvious that the choice of site is most important, and I am glad that proper attention has been paid to this subject.

In Section 3.3 there are remarks about staff costs, and with some pride the authors say that we have only three people on duty. I feel that this is still one too many; we should be able to reduce it to two. The time may perhaps come when the station can be completely unattended, as is the case with many of our sound transmitting stations.

The building may be criticized for being too generously designed and having too much spare space. When we designed the building we had great difficulty in meeting the requirements of the L.C.C.; moreover, we did not know what size transmitters we were going to install, so there had to be a fairly big factor of safety. Again, since it was to be a buried building, we wanted to make sure that we excavated enough for anything we might want later.

I should have liked the authors to include more description of the model aerial work done in the Research Department

* Lewis, N. W.: 'Waveform Responses of Television Links', *Proceedings I.E.E.*, Paper No. 1688 R, July, 1954 (101, Part III, p. 258).

determine the design of the aerial. It was interesting and portant work, and more information should be given about it.

Those who have seen the Crystal Palace station may wonder ly we have brought it into service with such a poor-looking rial. This aerial is very temporary, because we have been in gotiation for a long time with the Independent Television uthority on the possibility of their building a station adjacent to rs and erecting a Band III aerial on our tower. They have cepted our offer and for that reason the whole of the tower ove the 440 ft level is at this moment being redesigned and made. As a result, it will be some time before the complete rial as described in the paper will be ready.

There have been some comments already about the suitability the installation for colour, but I will not enlarge on them. I onder, however, whether the authors have anything further to y about possible changes which may be necessary if we wish radiate a colour service from the Crystal Palace transmitter.

Probably the most important point Dr. Rendall and Mr. Padel d in mind was the provision of a robust low-distortion circuit the transmitter of ample bandwidth for further expansion. is seems to have been achieved very successfully.

Mr. W. H. Devenish (*communicated*): As a 'user' of the tele- ion transmitters at Crystal Palace, I was distressed to hear no erence to the sound transmission, either in the introduction to e papers or in the discussion on them. The complete neglect this part of the transmission is perhaps a natural reaction to e corresponding lack of attention given to the subject by the 3C in its everyday activities. Any evening will provide aural idence of the truth of this statement.

Messrs. Cooper and Morcom describe improved black-level mping arrangements; will these result in any better correspon- nce between the setting of receiver controls for the best repro- ction of test card C, the tuning signal card which follows it, d the subsequent programme? Even after giving my set a rming-up period of approaching half an hour, I find that the ting of brightness and contrast controls is not worth while til the actual programme commences.

Mr. C. W. Earp (*communicated*): I am surprised that aerial in is obtained by the principle of vertical stacking only, par- ularly since space is required for several different aerials and werful excitation of the mast by different transmitters may lead cross-talk difficulties.

Messrs. McLean, Thomas and Rowden mention that certain vantages may be derived from the use of quadrature phase ationship of radiating element currents, but find that the tem is precluded by the large cross-section of the tower. My view is that polyphase radiation can derive particular advantage from the use of large dimensions in the horizontal plane. To demonstrate this, if eight vertical dipoles are uniformly spaced round a circle of $0{\cdot}75\lambda$ diameter, and are fed in cyclical order with currents of relative phase 0°, 90°, 180°, 270°, 0°, 90°, 180°, 270°, radiation in the horizontal plane shows a small gain over that produced by a single dipole, this gain being derived from suppression of high-angle radiation. Similarly, 16 dipoles on a circle about 1λ in diameter can be fed in similar manner to give a gain very near to 3 dB. In either case, a concentric mast of small cross-section compared with the aerial diameter is substantially unexcited, and causes no modification of the radiated pattern. Since in the present design, the lower half of the aerial is actually comprised of rings of eight dipoles, it appears at first that a considerable improvement might be obtained by a different method of feeding. Unfortunately the mast dimension at this height is too large for rings of eight dipoles.

Although a suitable circular horizontal pattern may be obtained by polyphased dipoles spaced closely to a circular mast of large dimension, or—with certain limitations—round a square mast, the mast may modify the radiation pattern in a manner which is detrimental to horizontal radiation gain. On the other hand, practical experience with this type of aerial has emphasized particular difficulty in obtaining high-angle radiation. A careful study of the problem has not been possible, and I can make no concrete proposal for improved performance. A new design must involve fresh considerations of windage and appearance, and I am not prepared to say that a new technique will permit overall performance to equal that which has already been obtained by the authors. One aspect which has not yet been considered in sufficient detail is the effect upon aerial frequency bandwidth, and I am conscious that design for maximum aerial gain does not correspond to maximum bandwidth. If, however, the polyphased array of large dimension has not been considered, I suggest that some future installation might derive benefit from the technique, even though a different type of tower might be necessary.

Meanwhile, if it should appear desirable to avoid strong excitation of the present tower, I would suggest consideration of the following. Both halves of the aerial could be associated with the 9 ft 6 in section of the present tower, and each could be comprised of two cophased tiers of 16 polyphased dipoles arranged on a diameter of about 22 ft. Correct relative phasing of radiating elements might be easier than for the present design, and an approximately equal aerial gain is likely to be achieved.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Messrs. F. C. McLean, A. N. Thomas and **R. A. Rowden** (*in ply*): In asking what precautionary steps were taken to avoid ception difficulties when transferring the service from Alexandra lace to the Crystal Palace, Captain Booth raised a point of eatest importance. Initial coverage measurements had shown it, while over a large part of the area there would either be an preciable gain or no significant loss of signal, over certain areas preciable loss of signal would occur. To anticipate trouble m this cause, the receiver industry and receiver distributors re fully informed as to the possible effect of the change, nted information was made available, including suggestions dealing with abnormally high or abnormally low signals, and blicity was also given in the television programmes, including nce-repeated talk.

The interleaving of Band I and Band III aerials is still being idied, but it is doubtful whether a satisfactory polar diagram both bands can be obtained with such an arrangement. However, if results appear promising, such an arrangement might be added to the Crystal Palace tower.

Replying to Mr. Strong, we agree that the advantages of paralleling transmitters are more apparent with high-power equipments and that it is probably not worth the complexity to parallel very-low-power transmitters. The outstanding advantage of paralleling is that there is no interruption to the service when a fault occurs on a single transmitter. With alternative transmitter operation, no matter how much the reserve transmitter is kept in standby condition, there is bound to be some interruption. Moreover, experience indicates that more faults occur when a transmitter is switched on than when it is running.

We would assure Mr. Strong that there was no special pleading in accepting a drop of 6 dB under a fault condition, since this point was checked by careful tests. It was realized that it was not desirable to remain operating in this loss condition and therefore arrangements were provided to reduce the loss to 3 dB.

Replying to Sir Harold Bishop, each doubling of the aerial aperture increases the gain by approximately 3 dB. The gain from four to eight stacks is therefore achieved by increasing the height of the aerial by approximately 80 ft, with an increase in the mean height, however, of only 40 ft. A further 3 dB would have meant an increase in height of a further 160 ft, with an increase in the mean height of 80 ft. It is therefore an extremely expensive matter when there is no limit to the overall height. When, however, there is a limit, an increase in the aperture actually means a decrease in the mean height and hence an appreciable loss of radiation efficiency from the aerial system. With these factors in mind, an aperture of eight dipoles was found to be the most advantageous.

Sir Harold mentioned an apparent discrepancy between Table 1 and the figures given in the text. The figures in the Table were derived from theoretical studies, whereas those in the text were obtained from actual measurements.

The design of the aerials was verified with scale-model experiments at approximately ten times the working carrier frequencies, carried out in the B.B.C. Research Department.

Sir Harold also asked for further information about possible changes which might be necessary if it were desired to radiate a colour service of the N.T.S.C. form from the Crystal Palace transmitter. The modifications required are expected to be of a comparatively simple nature. As stated in the paper by Messrs. Cooper and Morcom, the modulator will be able to deliver the extra power required by the high levels of modulation at the sub-carrier frequency which are inherent in the N.T.S.C. system. A relatively slight modification to the black-level clamp circuit (at the input to the modulator) would also be required. In addition, the existing signal-correction units (which include the synchronizing-pulse-stretching and stabilizing circuits and the linearity-correction circuits) are unsuitable for colour signals and would have to be replaced by alternative units designed to pass N.T.S.C. type signals. A unit would also be added to the r.f. drive equipment for locking the sound and vision carrier frequencies together, so that they would bear the necessary relation to ensure a minimum of interference on the picture caused by the beat between the sound carrier and colour-modulated vision carrier. As stated by Captain Booth, no decision as to the radiation of an N.T.S.C. type of signal or any other form of colour signal has as yet been taken by the Television Advisory Committee.

Mr. Earp makes the interesting suggestion that by the use of polyphase-fed tiers a greater gain could be obtained within the same aerial aperture. We think, however, that such an arrangement would not be desirable for broadcasting use, because

(*a*) Although a polyphase tier could probably be designed to have a gain of 3 dB, four such tiers when operated together would give a gain very little greater than four tiers of zero gain.

(*b*) The use of 16 dipoles would involve very difficult mounting arrangements; the complexity of these and of the feeder arrangements would outweigh any possible gain.

(*c*) The mechanical loading of the mast due to the larger number of dipoles would be very much increased.

Replying to Mr. Devenish, the absence of details of the sound transmitter in the paper is not an indication that this side of the transmission was neglected. The equipment, however, is largely in accordance with accepted practice of good sound-transmitter design, and hence it was not thought advisable to take up space with a detailed description. The performance of the two sound transmitters is fully up to the highest standards.

Dr. A. R. A. Rendall and **Mr. S. H. Padel** (*in reply*): The slight lift of the trailing corners of the T and $2T$ pulses to which Mr. Macdiarmid refers was subsequently corrected by means of a small equalizer to give the T and $2T$ pulse responses shown in Figs. 9(*d*) and 9(*e*) of the paper. It is perhaps interesting to note that before correction this small distortion showed up on the line-bar waveform on the corners following transitions from black to white and vice versa, and in the steady-state amplitude/frequency response by a dip of 0·2 dB between 1·0 and 1·5 Mc/s. The equalizer corrected this to give the system performance published in the paper.

We would be the first to agree with Mr. Macdiarmid that the figures quoted for linearity would be unsuitable for a 500-mile chain of links. The performance specification in Section 2 does not refer to this, but to the particular short link for which the system was designed.

Messrs. V. J. Cooper and **W. J. Morcom** (*in reply*): We thank Captain Booth for his remarks on the paralleling and phasing of the transmitters. Since the station is manned continuously during operation, it was not considered that the small degree of phase drift, known to exist from our laboratory experiments, justified automatic control. The degree of phase constancy specified by the B.B.C. is, in fact, comfortably achieved without automatic control.

Automatic phasing has been used on f.m. transmitters on Band II quite successfully, and this will be dealt with in a future paper. The paralleling on Band III transmission is at present the subject of laboratory tests which indicate that it should be equally successful.

Sir Harold Bishop states that the power of the Crystal Palace transmitter is only twice that of the Alexandra Palace station of 20 years ago and that he does not know whether this means that nearly all the improvements in performance are to be found in the aerial. The power output of a transmitter is a matter of specification: hundreds of kilowatts are possible, but in this instance very high power was not considered to be necessary and the B.B.C. specified 12 kW peak power for each vision transmitter.

Compared with the original Alexandra Palace transmitter the performance of the Crystal Palace transmitters has been improved in many respects. One aspect of particular interest and importance is the improved overall power conversion efficiency of the transmitter. The Alexandra Palace transmitter had a conversion efficiency of 10–12%; in the first post-war designs in this country this was improved to 18–20%; the corresponding conversion efficiency of the Crystal Palace transmitters is 33%. This improvement in power consumption is due almost entirely to the use of the shunt-regulated amplifier technique in the modulator circuits, and to the use of tetrodes. Furthermore, present-day transmitters of a given power have considerably more power output available to deal adequately with colour sub-carrier requirements.

In the transmission of colour television of the N.T.S.C. type modifications to the transmitter are of negligible magnitude, as indicated in Section 6 of the paper. Where colour transmission is anticipated these features are incorporated in the basic design with negligible effect on monochrome performance.

We have every sympathy with Mr. Devenish who finds that a given receiver setting on Test Card C does not remain optimum during a performance. This is not due to the stability of the radiated black level in the waveform—which we assure him remains within the specified 2%. It is due (*a*) to the difficulty in camera channels of maintaining 'picture black' in constant relation to 'waveform black', commonly referred to as 'sit up', (*b*) to the fact that many modern receivers do not use fully the d.c. information in the received picture, and therefore 'black' and 'white' are displayed as relative rather than as predetermined brightness values. In the majority of cases this technique is an alleviation of, rather than a contribution to, the effects referred to by Mr. Devenish, but for the more critical observers it can contribute to undesirable brightness distortions.

.385.032.213

Paper No. 2140 R
Sept. 1956

NOTES ON A SOURCE OF INTERMITTENT NOISE IN OXIDE-CATHODE RECEIVING VALVES

By M. R. CHILD, Associate Member.

(*The paper was first received* 17*th January, and in revised form* 4*th May*, 1956.)

SUMMARY

A source of intermittent noise in oxide-cathode receiving valves is entified with the presence of variable leakage paths between certain ectrodes. The dependence of this phenomenon on valve parameters discussed and mention is made of an improvement in valve design hich inhibits the growth of inter-electrode leakage.

(1) INTRODUCTION

The last few years have witnessed an improvement in the useful e of high-slope thermionic valves suitable for use in industrial uipments. The resistive interface layer which tended to evelop between cathode core and matrix has been partially iminated, and improved degassing of valve piece-parts has led some improvement in stability of cathode emission. As a sult of these improvements, however, it seems that the valve gineer may have to contend with secondary sources of valve ilure which have become increasingly noticeable with the nprovement in life. One of these is the development of inter-ittent noise. This type of noise has been observed in a diversity f valve types. It is comparatively rare in commercial valves ut is frequently encountered in high-grade valves in which the anufacturing requirements contribute towards the conditions ssociated with the inception of the noise. The effect can be vestigated by measuring the noise level in the frequency range)–1 000 kc/s and expressing it in terms of an equivalent grid esistance. It has been demonstrated that under certain con-itions this resistance may approach 100 000 ohms.

The object of the paper is to discuss various parameters fecting the form and level of the noise, to offer an explanation or its existence and to suggest a means of avoiding it in future alve designs.

(2) NATURE OF THE NOISE

Investigations into the characteristics of the type of valve noise nder discussion were mainly confined to the frequency range)–1 000 kc/s. It was observed that throughout this spectrum e waveform approximated to that of shot noise with the ddition of short-duration pulses at a relatively low repetition te. The term 'spike noise' is used to denote all forms of traneous valve noise which are characterized by narrow pulses f energy, but it is thought that a sub-division of these noise fects may be useful and the term 'l.a.m. effect' has been applied this particular form of noise. The reason for the choice of omenclature will become obvious later.

The amplitude of the noise produced by l.a.m. effect has been easured in terms of an equivalent grid resistance and the aximum observed value was 100 000 ohms. It is possible only general terms to describe how this form of noise will occur, nce it is dependent upon a number of parameters, including alve geometry, the materials used in the manufacture of the alve and the supply voltages. The following description is irly typical of good-quality pentodes designed to operate with $_h = 6\cdot3$ volts, $V_a = V_{g2} = 250$ volts and $I_a = 6$ mA, and may e used as a guide to the problem.

Written contributions on papers published without being read at meetings are vited for consideration with a view to publication.

Mr. Child is at the Post Office Research Station.

The noise is not generally present in new valves but appears spasmodically as the valves age. An increase in both the level and the duration of the noise is noticeable as the valve life extends into thousands of hours, but in many cases the noise disappears entirely after some tens of thousands of hours.

A description of the methods employed to localize the source of noise is given below.

(3) EXPERIMENTAL INVESTIGATION OF THE ORIGIN OF THE NOISE

(3.1) Experimental Technique

The most suitable form of equipment for investigating the l.a.m. effect proved to be a standard item already in use for measuring shot noise. The valve under test was placed in the first stage of a high-gain amplifier, the output of which was measured on a microammeter after suitable rectification. The control grid of the input valve was first connected to earth and the reading on the output meter was noted. A resistance of known value was then introduced between the control grid and earth, and the increase in noise level at the output enabled a simple computation of the equivalent grid-resistance noise to be made. For example, let the equivalent resistance be R_{eq}, and let the added resistance be R. Then if the increase in noise power is n times, it follows that $R_{eq} = R/(n - 1)$.

Two types of amplifier were used. One was sharply tuned to 100 kc/s and provided spot checks as described above. The second amplifier covered the frequency range 20–1 000 kc/s with a sharp cut-off at the lower end to avoid microphonic effects. A recording microammeter was connected at the output, and observations of noise level were thus made over very long periods.

The wide-band amplifier and recording equipment were used to investigate the effect of valve parameters on this form of noise.

(3.2) Dependence of Noise Level on Valve Parameters

Sequential loading of the various electrodes indicated that the noise level was primarily dependent upon the anode voltage, dependent to a lesser extent upon the cathode temperature and virtually independent of all other electrical parameters.

In particular cases it was seen that the noise output continued without any appreciable change in level when the cathode circuit was disconnected. A section of the chart attached to the recording ammeter referred to in Section 3.1 is reproduced in Fig. 1 to demonstrate this point. The noise amplitude appears as a deflection of the needle away from the right-hand zero, and in this particular case a full-scale deflection represented an equivalent grid-resistance noise of 10 000 ohms. The chart speed was 6 in/h. With the cathode circuit disconnected the noise level varied as a function of anode potential over the range 100–300 volts. At anode voltages of less than 100 volts only about 5% of the samples exhibited noise in excess of their normal short-noise level, and no cases have so far been observed in which the l.a.m. effect could be detected at anode voltages of 60 volts or less. It should, however, be mentioned here that the only samples examined with anode voltages below 60 volts all had oxide-coated platinum cathodes, a fact which may have accounted for the better noise performance.

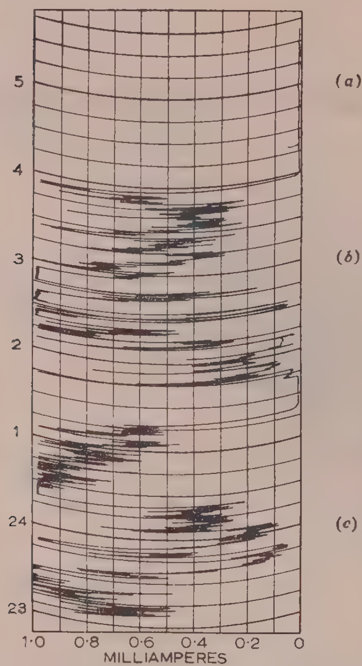

Fig. 1.—Chart showing intermittent noise output and its dependence upon leakage path between anode and suppressor.

(a) Cathode and suppressor grid disconnected.
(b) Cathode disconnected.
(c) Normal operation.

(3.3) Link with Inter-Electrode Leakage

The persistent high noise level observed at the anodes of a number of samples operating with disconnected cathodes eliminated the possibility of a noisy electron stream and focused attention on the insulation between electrodes. In practically every case in which valve noise was present a corresponding intermittent flow of current was observed between the anode and some earthy point in the valve, and the noise ceased whenever the earthy electrode was disconnected (see Fig. 1). The most common path was between the anode and an internal screen or the suppressor-grid supports. The noise was not related to the magnitude of the leakage current but rather to its instability.

Throughout the life of the valve, barium and magnesium evaporate from the hot cathode and anode and condense in the form of conducting metal films on the insulating surfaces of the valve structure. At the same time, oxidizing residual gases are released to a greater or less extent from the structural components and their gas action tends to destroy the conductivity of the films. The final outcome depends on the balance of residual gas on the one hand and metallic evaporation rate on the other, and it follows that the better the initial processing of the valve the greater is the probability of early appearance of a conducting film.

There are two possible insulated paths between electrodes across which the metallic films could form, namely the glass pinch and the supporting micas. The use of a double-ended valve in which the anode was connected to the top cap, thereby increasing the glass path between that electrode and all the others by a factor of 100, did not affect the noise level. However, a single-ended version with short glass paths between electrodes but with the anodes suspended without the aid of micas provided a noise-free valve. From these experiments it was concluded that this particular form of 'spike' noise was caused by leakage across the micas and it was decided to identify it by th initials l.a.m.

(3.4) Effect of Valve Materials on Inter-Electrode Leakage

The rate of growth of leakage and noise in valves having activ nickel cathode sleeves is found to be about 10 times as fast a the corresponding rates in valves with platinum cathode sleeve This difference may be attributable to the fact that the nick sleeves contain reducing agents which assist in maintaining liberal supply of free barium. It has recently been suggested i an unpublished work by C. B. Johnson, however, that magnesiu is liberated from the nickel anodes under certain working con ditions. If this is the source of leakage deposits in the platinum cored valve, it is probable that an improvement greatly in exce of 10 times can be achieved by suitable choice of anode materia So far, there has been no opportunity to attempt a correlation o this point.

Another factor involved in the growth of leakage paths is th state of the mica surfaces. In commercially produced valve the micas are coated with magnesia, thus providing a roughene surface of much greater path length between the electrodes. Th improvement obtained seems fully to justify the practice in thes valves.

The effectiveness of the coated micas was demonstrated on quantity of double triodes in which one triode section wa mounted on sprayed micas and the other on untreated mica Twenty-four valves were run on the wide-band recording appa ratus after a preliminary period of ageing. The triodes wit uncoated micas provided a noise-output power between 2 an 10 times as great as that of the triodes with treated micas.

On the evidence to date there seems to be no reasonable doub that a high level of noise can be expected at the anode of a wel processed high-quality valve at some stage during its life if th anode voltage exceeds 100 volts. Since there are a number applications in which such a valve must be operated with anod voltages in the neighbourhood of 200 volts, it is necessary t attempt to find a solution to the problem.

(4) EXPERIMENTAL ARRANGEMENTS TO AVOID NOISE DUE TO L.A.M. EFFECT

One obvious cure, already mentioned, for this form of noise to isolate the anodes from the micas which support the rest the assembly. This arrangement, whilst electrically sound, difficult to achieve mechanically without seriously weakening th valve structurally. An obvious alternative method which ha been tried successfully, consists of interposing shields so locate that material evaporated from the cathode or the anode cann collect on the micas to form continuous paths between th critical electrodes.

(5) CONCLUSIONS

One form of 'spike' noise in high-grade valves is shown to b due to intermittent leakage between electrodes caused by th deposition of barium or magnesium, or both, on the supportin micas. The magnitude of the effect is shown to increase wi the anode voltage between 100 and 300 volts. No effect can b detected below 60 volts in the case of passive cores. The effe may be successfully avoided by the use of mica shields.

(7) ACKNOWLEDGMENTS

The author wishes to express his thanks to the Brimar Valv Division of Standard Telephones and Cables Ltd., for providi many of the special valves used in this investigation. Ackno ledgment is made to the Engineer-in-Chief of the General Po Office for permission to make use of the information containe in the paper.

21.317.382

Paper No. 2125 R
Sept. 1956

ABSOLUTE CALIBRATION OF A STANDARD TEMPERATURE NOISE SOURCE FOR USE WITH S-BAND RADIOMETERS

By V. A. HUGHES, M.Sc.

(*The paper was first received* 26*th September*, 1955, *and in revised form* 14*th March*, 1956.)

SUMMARY

To provide a standard temperature noise source for use with S-band radiometers, the noise power from the argon discharge tube CV1881 has been calibrated at 2 860 Mc/s using radiometer techniques. The absolute value of the effective temperature of the tube with a discharge current of 180 mA, when mounted across a waveguide parallel to the E-plane and properly matched, is 11 140° K (15·73 dB) with a maximum error of 260° K (0·10 dB), and represents a considerable improvement in accuracy over previous measurements. Since this tube shows a high degree of stability and consistency, it is suggested that it could be used as an absolute standard noise source for the measurement of the noise factor of receivers.

(1) INTRODUCTION

Standard noise sources are requirements in centimetric radiometers both as comparison sources and for calibration. It is possible to use heated loads for temperatures up to about 500° K, but apart from the general inconvenience of having to provide temperature-controlled ovens, difficulty arises if rapid changes of temperature are required. One form of temperature source that has been developed in recent years is the discharge tube, and by using it in series with a variable attenuator, it should be possible to obtain effective temperatures from room temperature up to about 10 000° K or more merely by adjusting the attenuator. The accuracy of the temperature source depends both on the resetting accuracy of the attenuator as well as the absolute calibration of the effective temperature of the discharge tube.

In the past, the calibration of discharge tubes in the S-band has been made by comparison with c.w. sources, but owing to the large difference in power level between the standard c.w. sources and the thermal noise powers involved, the accuracy of calibration has not been very high. The commonly accepted value for the argon discharge tube CV1881 is 15·5 dB,* obtained from the results of Johnson and De Remer,[1] who claimed an accuracy of ±2 dB, and from other unpublished results where the accuracy has been about ±1 dB. Since it has been found possible to obtain attenuator accuracy of ±0·01 dB, it was decided to calibrate discharge tubes against the noise from a heated load in order to obtain more accurate values for the effective temperature.

This paper describes the equipment and the results obtained during the calibration of the argon discharge tube CV1881 in an E-plane mount at 2 860 Mc/s. Having thus obtained a standard temperature source, measurements were made against mercury-vapour tubes. No attempt is made to describe the physical processes taking place in the discharge.

(2) THE RADIOMETER TECHNIQUE

Radiometers for radiation measurements at microwavelengths are basically equipments for measuring small noise powers. In order to reduce the effect of gain variations, the receiver is used to measure the difference in level between two sources of noise, and in the ideal case takes the form of a null detector. In the original microwave radiometer constructed by Dicke[2] the noise source was compared with thermal radiation at room temperature by periodically inserting a disc of attenuating material into the waveguide between the noise source and receiver, and measuring the difference in receiver output, the comparison being made at about 30 times a second.

In the present equipment a waveguide switch is used to compare the radiation from a hot load with that from a discharge tube and calibrated attenuator, and the attenuator is adjusted until the radiometer output indicates that both sources are approximately equal. From the measured parameters of ambient temperature, attenuator setting and load temperature, the discharge tube is calibrated and the standard temperature source is obtained.

(3) THE EQUIPMENT

(3.1) The Radiometer

The radiometer is shown diagrammatically in Fig. 1. The switch consists of a T-junction and two discs which rotate on a spindle and alternately cut the arms of the T, allowing power to be received from each in turn, the discs being cut from Perspex and covered with aluminium foil. On the same spindle is mounted a further disc, arranged so that by means of a lamp and photocell a reference voltage can be obtained at the same frequency as the switching frequency. The spindle was driven by a synchronous motor controlled from a tuning fork, which was found advisable since variations in mains frequency produced drifts in the output of the radiometer. The gearing from the motor to the spindle was such that the switching frequency was about 30 c/s.

The balanced mixer consisted of a rat-race and two crystal detectors, and in order to reduce noise modulation from the crystals due to small changes in matching as the switch rotated, one of the crystal arms was made $\lambda/4$ longer than the other. A further source of noise modulation is reflection of local oscillator power from the switch, and this was eliminated by using a cavity, tuned to the centre frequency of 2 860 Mc/s, between the switch and the mixer. The cavity has the added advantage that it eliminates one of the sidebands, and allows the arms of the switch to be matched to a voltage standing-wave ratio of better than 0·99.

The receiver side of the radiometer consisted of a 45 Mc/s i.f. strip, a 30 c/s tuned amplifier, a phase-sensitive detector and an output stage, the output being displayed on a 0–1 mA recorder. The noise level at the recorder was such that it was possible to detect temperature differences of 0·5° K between the two arms of the switch.

(3.2) The Hot Load

Attempts were made to construct loads which could be heated to about 300° C or more without variation in matching, and of reasonably short length so as to reduce temperature gradients. It was finally decided to use the standard type of load developed

* The effective temperature of discharge tubes is often expressed as the ratio, in decibels, of the noise in excess of room temperature to the noise from a room-temperature source, where room temperature is assumed to be 290° K. This convention is used in the text when temperature is referred to in decibels.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Hughes is at the Radar Research Establishment.

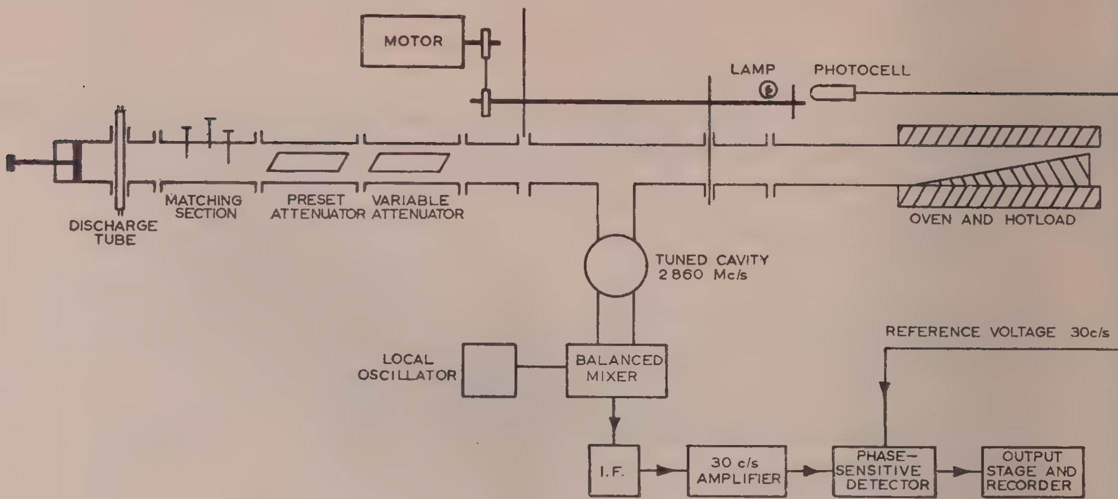

Fig. 1.—Block schematic of radiometer.

by Halford and Miles.[3] This load, which consists of a mixture of iron dust and Marco resin, was able to withstand a temperature of 250° C, but some resin distilled into the waveguide. Before use, the load was placed in an oven and kept at a temperature of 250° C for a few hours until the distillation had ceased.

To ensure uniform temperature over the length of the load, three copper-Constantan thermocouples were first calibrated against good thermometers. The thermometers were taken from various batches, and initially compared against each other at room temperature, those showing obvious errors being discarded. The remainder were again compared at the temperature of boiling water and were then placed in hot wax and heated to 250° C, those thermometers which deviated by more than 1° C from the mean being discarded; the final three thermometers were consistent to within 0·5° C. Adopting the standard method of calibration, the hot junctions, together with the three thermometers, were placed in a bath of wax which was heated to 250° C, while the cold junctions, together with a further thermometer, were covered in cotton wool; the thermo-electric e.m.f. was then plotted against the temperature difference between junctions at intervals of about 5° as the wax cooled.

The thermocouples were embedded in the load, two on the underside, at the front and rear, and one about the middle of the upper side.

The oven was constructed from a length of waveguide, by winding resistance wire round the outside. Mica sheets were used to insulate the wire from the metal surface of the guide and to protect the outer covering of asbestos string. The overall length of the oven was about 20 in, and the load, which was about 10 in long, was placed in the centre; the thermocouple leads were brought out through a heat-insulating plug at the end. Power was supplied to the heating element through a variable transformer from the mains, and it was found that a current of about 3·5 amp was required to maintain a temperature of about 250° C.

(3.3) The Standard Temperature Noise Source

The standard noise source to be calibrated consisted of the discharge tube and its holder, the matching section and an attenuator.

To increase attenuation accuracy, two Nichrome-sprayed, glass-vane attenuators were assembled in a preset attenuator mount and a variable attenuator respectively. The preset attenuator was set to about 10 dB, and the attenuation required, which was in the range from about 17 to 27 dB, was adjusted by means of the variable attenuator.

It was found that for a resetting accuracy of 0·01 dB the vanes had to be positioned to within 0·000 3 in, and that the existing scale on the variable attenuator was not accurate enough to allow this. The mount was thus modified by incorporating a micrometer head and tensioning spring, and by taking precautions against backlash, the required setting accuracy was achieved.

The resetting accuracy and calibration of the composite attenuator was obtained using a precision attenuator calibrator.[4] The principle of the method is that variations in radio-frequency power are measured by converting to an intermediate frequency of 60 Mc/s and then comparing with a signal obtained from a stabilized oscillator, varied by means of a piston attenuator. By this means relative variations in attenuation are obtained to an accuracy within 0·01 dB.

The absolute calibration was obtained by taking a zero reading from the piston attenuator when a length of waveguide, equal to the length of the attenuator assembly, was in circuit. This length of waveguide was then removed and replaced by the attenuator. It was found that over a series of four sets of measurements, using various sections of the piston-attenuator scale, the maximum deviation in the calibration was 0·01 dB for attenuations between about 17 and 27 dB.

The discharge tubes were mounted at 90° to the direction of propagation along the waveguide. The method followed in matching was initially to adjust a plunger at the rear of the tube to give the best v.s.w.r.; final adjustments to give a v.s.w.r. of better than 0·99 were made by tuning screws in front of the tube.

(4) METHOD OF MEASUREMENT

(4.1) Calibration of Standard Temperature Noise Source

The discharge-tube mount and attenuator were assembled and connected to one arm of the switch and the oven and load to the other; both arms were matched so that the v.s.w.r. at the mixer was better than 0·99 with the switch in either position. With the discharge tube off, the attenuator set to its maximum value and the attenuator and load at roughly equal temperatures, the recorder output was noted. In all cases the recorder indicated the correct temperature difference between the attenuator vane and load to within 0·5° C, checked that there were no spurious

ignals and showed that the equipment was operating satis-ctorily. The recorder chart was accurately calibrated by vitching on the discharge tube with the attenuator arbitrarily t to a value of 27·85 dB. The load was then heated, the tenuator was set so that the recorder output indicated approxi-iately equal temperatures, and, with the three thermocouples idicating that the load was at a uniform temperature, readings ere taken of the load temperature, the attenuator temperature nd setting, and the recorder output. It was found convenient calibrate the attenuator for settings corresponding to increases temperature of approximately 20° K, and to take a series of adings with the load at temperatures in the range 160–230° C.

The temperature of the discharge tube was arrived at as follows:

Let T_D = Effective temperature of discharge tube.
T_L = Temperature of heated load.
T_0 = Temperature of attenuator.
α = Attenuation setting when taking a reading.
β = Attenuator value for initial recorder calibration.
R = Deflection of recorder during the initial calibration.
X = Deflection of recorder when taking reading with hot load.
δT = Temperature difference as indicated by deflection X.

he effective temperature of the discharge tube and attenuator ay be shown to be equal to

$$\frac{T_D}{\alpha} + \left(1 - \frac{1}{\alpha}\right) T_0$$

nd the temperature difference is given by

$$\frac{T_D}{\alpha} + \left(1 - \frac{1}{\alpha}\right) T_0 - T_L = \delta T \quad . \quad . \quad . \quad . \quad (1)$$

he difference δT is obtained from the initial calibration, since he deflection, R, is due to an increase in temperature of $(T_D - T_0)/\beta$. The difference in temperature, δT, is hence iven by

$$\delta T = \frac{X}{R\beta}(T_D - T_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

ubstituting eqn. (2) into eqn. (1) and transposing terms, the ffective temperature of the discharge tube is given by

$$T_D - T_0 = \frac{T_L - T_0}{\dfrac{1}{\alpha} - \dfrac{X}{R\beta}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(4.2) Comparison Measurements

With the standard temperature source calibrated, measure-nents were made with other argon tubes and with mercury-apour tubes. For these measurements a comparison source vas constructed which consisted of a directional coupler with a oupling ratio of about 15 dB. The direct arm was terminated vith a dummy load and the coupling arm with an argon tube vhich, using the radiometer, had been previously compared with, nd found sensibly equal in effective temperature to, the standard ube. The oven was replaced by the comparison source and alibrated against the standard source. Comparison measure-nents could now be made by replacing the standard tube by any f the other tubes, large differences in effective temperature being ompensated for by adjustment of the attenuator.

If the effective temperature of the comparison source is T_c, he attenuator setting to approximate this is α_1, and the difference temperature as measured at the output of the radiometer is T_1, then

$$\frac{T_D}{\alpha_1} + \left(1 - \frac{1}{\alpha_1}\right) T_0 - T_c = \delta T_1 \quad . \quad . \quad . \quad . \quad (4)$$

If the standard tube is now replaced by a tube with effective temperature T', and the new temperature difference is δT_2 with attenuator setting α_2,

$$\frac{T'}{\alpha_2} + \left(1 - \frac{1}{\alpha_2}\right) T_0 - T_c = \delta T_2 \quad . \quad . \quad . \quad (5)$$

The effective temperature of the new tube is thus given by

$$T' - T_0 = \frac{\alpha_2}{\alpha_1}(T_D - T_0) + \alpha_2(\delta T_2 - \delta T_1) \quad . \quad . \quad (6)$$

(5) RESULTS

(5.1) Argon Tubes E-Plane Mount

Four series of measurements were made consisting of 19 determinations of the value of T_D for an argon discharge tube CV1881 drawing 180 mA in an E-plane mount: the mean value obtained was 11 090° K (15·71 dB) with an r.m.s. deviation of 110° K (0·04 dB). To check the symmetry of the switch, the standard temperature source was interchanged with the hot load, and a new set of 18 measurements were taken. The mean value obtained was 11 190° K (15·75 dB) with an r.m.s. deviation of 87° K (0·03 dB). Since the two values obtained are within 1%, and this difference may be attributed to a possible lack of symmetry in the switch, the mean of the two readings is taken. The mean value for the absolute temperature of the discharge tube is hence 11 140° K (15·73 dB) and the r.m.s. deviation of all the readings 110° K (0·04 dB).

To check the variation in effective temperature of other argon tubes run under the same conditions as the standard, the hot load was replaced by the comparison source. The standard tube was removed from the mount and replaced in turn by four other tubes. The effective temperatures were 15·70, 15·75, 15·73 and 15·73 dB.

The variation in temperature of the standard tube with change in current was then measured against the comparison source, the current through the tube being varied in steps of 20 mA from 140 to 240 mA. After each current adjustment the tube was rematched by means of the tuning screws. The relative variation in effective temperature obtained was plotted against tube current and is shown in Fig. 2, from which the mean coefficient for change in effective temperature with current is −0·004 dB/mA.

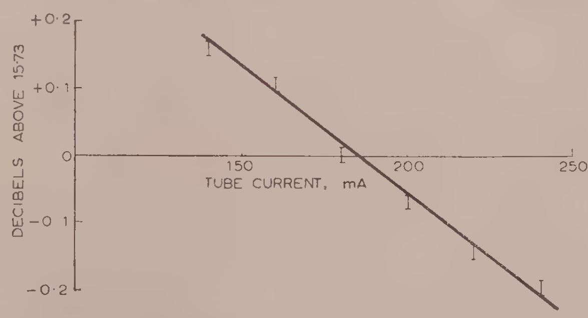

Fig. 2.—Variation of effective temperature with discharge current: argon tube in E-plane mount.

(5.2) Mercury-Vapour Tubes in H-Plane Mount

Three mercury-vapour discharge tubes with the same dimensions as the argon tube were available, two commercial tubes with fluorescent coatings and one clear tube. With all tubes the effective temperature drifted during a period of about 20 min after switching on, showing a general decrease with time, and one tube had not become stable after three hours. It has been

suggested by Mumford[5] that the effective temperature of the mercury-vapour tube is a function of ambient temperature. Measurements of change in effective temperature with ambient temperature were not made, but it was noted that the matching of the tube changed appreciably with time. A tube was allowed to run continuously for about 6 hours and then matched for a v.s.w.r. of about 0·99. The following day the tube was restruck and the change in matching noted. Initially, the v.s.w.r. was 0·63, in the first 10 min it fell to 0·52, and after 110 min it had returned to 0·91. It was decided to take approximate measurements only of the effective temperatures, in order to provide a comparison with the argon tubes.

The method of measurement was to switch on the tube, allow it to run for 20 min, match the tube and then take a measurement. The results showed that for discharge currents of 100 mA the tubes with fluorescent coatings had effective temperatures of 16·0 dB, whilst the clear tube gave a value of 16·2 dB.

(6) ERRORS

(6.1) Argon Tubes

The method of calibrating was such that errors were reduced to a minimum, and the scatter in the readings agrees well with that expected from random errors in the measured parameters. However, systematic errors may arise, and these will be treated in detail.

(6.1.1) Impedance Changes and Recorder Measurement.

The switch was carefully matched for a v.s.w.r. of better than 0·99, but to check the effect of impedance changes a mismatch with a v.s.w.r. of 0·85 was deliberately introduced into one arm of the switch. On varying the phase of the mismatch, the maximum change in the recorder reading corresponded to $\pm 3°$ K (0·07 dB in the value of T_D). Furthermore, the initial measurements showed that the recorder output agreed with the temperature difference in the arms of the switch to within the limit of measurement of 0·5° K. Hence the largest systematic error in measurement due to matching and recorder reading may be taken to be less than 0·01 dB.

(6.1.2) Attenuator Calibration.

Random errors in attenuator setting and in the precision attenuator calibrator were taken into account in the method of calibrating. Moreover, the comparison noise source agreed in temperature with the calculated value obtained from measurements on the coupling ratio of the directional coupler to within 0·01 dB. However, it is possible that a further systematic error of about 0·01 dB may be introduced due to mismatches and mechanical tolerances in the precision attenuator calibrator.

(6.1.3) Temperature Measurements.

Possible systematic errors are likely to arise in measurement of the temperature of the glass vane of the attenuator, in the calibration of the thermocouples and in possible temperature gradients along the hot load. By using three thermocouples along the load, and by careful control of the heating of the waveguide oven, the error from this source should be less than 0·5° K, but this should be taken into account in the random errors. The attenuator-vane temperature was measured by means of thermometers in contact with the outside wall of the waveguide, and care was taken to protect the guide from external air currents, so that the temperature remained sensibly constant over periods of about an hour. It is possible, however, that an error of 0·5° K may have existed between the thermometer reading and the temperature of the vane. Thermal coupling between the hot load and the attenuator will be negligible, since the two arms of the switch are effectively isolated by the Perspex vanes. The largest error is liable to occur in the absolute temperature calibration of the thermocouples, and it seems reasonable to assume that this may be about $\pm 1\cdot 0°$ C at 200° C. Hence, the probable error in the measurement of $T_L - T_0$ may be taken to be $\pm 0\cdot 04$ dB.

(6.1.4) Variation in Tubes.

The tubes used were all production-type CV1881's; of the six measured, only two deviated from the mean value, by 0·02 and 0·03 dB respectively, and it seems reasonable to assume that the probable error due to selecting tubes at random may be less than 0·02 dB.

(6.1.5) Losses in Holder and Matching Section.

From measurements on the v.s.w.r. of the discharge-tube holder and matching section, the maximum loss is estimated to be less than 0·01 dB.

Combining the systematic errors, the probable error in the final result is estimated to be $\pm 0\cdot 05$ dB (130° K), and the maximum error less than $\pm 0\cdot 10$ dB (260° K).

(6.2) Mercury-Vapour Tube

The accuracy of measurement of the effective temperature of the mercury tubes should be of the same order as that for argon tubes, but owing to the drift in effective temperature with time, no significance can be attached to the value of effective temperature inside the limits of about $\pm 0\cdot 2$ dB, since the time and ambient-temperature dependence was not measured.

(7) CONCLUSIONS

The absolute effective temperature of the argon discharge tube CV1881, when used in an E-plane mount with a discharge current of 180 mA, has been determined at 2 860 Mc/s, the value being 11 140° K (15·73 dB) with a maximum error of 260° K (0·10 dB). The measurements were made by comparing the radiation from the tube in series with an attenuator, with that from a heated load. Comparison measurements with fluorescent-material-coated and clear mercury-vapour tubes gave values of 16·0 and 16·2 dB respectively. The CV1881 shows remarkably good stability and consistency between tubes, and although the measurements were made in order to produce a variable temperature noise source for use with radiometers, the tube should also provide an ideal standard noise source for measuring the noise factor of microwave receivers.

(8) ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to Dr. J. S. Hey for encouragement and advice, and to Messrs. C. Baron and N. Houlding for helpful discussion. Acknowledgment is also made to the Controller of Her Majesty's Stationery Office for permission to publish this paper.

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NOISE MEASUREMENTS IN THE 3-CM WAVEBAND USING A HOT SOURCE

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SUMMARY

The method discussed uses the noise power produced in a waveguide rmination at temperatures up to 600° C as a standard source of low-vel power. A suitable type of hot source and associated waveguide nd detecting circuits are described. Some experimental results are ven of measurements on the effective temperature of a gas-discharge ibe used as a secondary standard source.

(1) INTRODUCTION

Standard methods of measuring power and methods of cali-rating signal generators have been described by a number of uthors. Two basic methods are in use—the mechanical tech-ique described by Cullum[1] and the more common calorimetric nethod.[2,3] A recent paper by Gordon-Smith describes the xtension of the calorimetric method to power as low as a few nilliwatts.[4] This probably represents the lower limit at which ccurate measurements can be made, and a more usual level for ower measurement is in the region of 1 watt or more. There s, however, a wide and important class of measurement at a nuch lower level. Consider in this connection a receiver with a oise factor of value 10 and a bandwidth of 1 Mc/s, working with n output signal/noise ratio of unity. The input signal power is $\times 10^{-14}$ watt. A signal generator used to supply this signal nust rely on the accuracy of an attenuation of about 140 dB. here appears, then, to be a need for a standard signal at very ow power level in order to relieve the severity of this extra-olation. Such a standard is available from a termination heated o a known temperature, the available power in watts per unit andwidth being kT, where k is Boltzmann's constant and T is he absolute temperature of the termination.

Hot devices are, in general, inconvenient to manipulate, not eadily transportable and slow to reach their operating tem-erature, so it is expedient to use the standard source to calibrate more convenient secondary source. Gas-discharge tubes have een in use for some years as noise sources for testing receivers,[5] and one type, the CV 1881, has proved to possess the various requirements for such an application to a very high degree. A series of careful measurements on the effective temperature of the CV 1881 is reported by Houlding,[6] who used the conventional sinusoidal-signal generator technique. It was therefore thought that a series of measurements using a hot source as the primary standard would be a logical step in the field of microwave measurement.

The principle of using a hot termination as a standard source is by no means novel,[7,8,9,10,11] and the main interest in the proposed measurements was in the degree of precision which the method can give.

(2) DESCRIPTION OF APPARATUS

The general arrangement of the apparatus for the experiment is shown in Fig. 1. Standard type-16 brass waveguide is used throughout except in the hot source, which requires steel. Connection between sections is by means of standard choke and flange couplers.

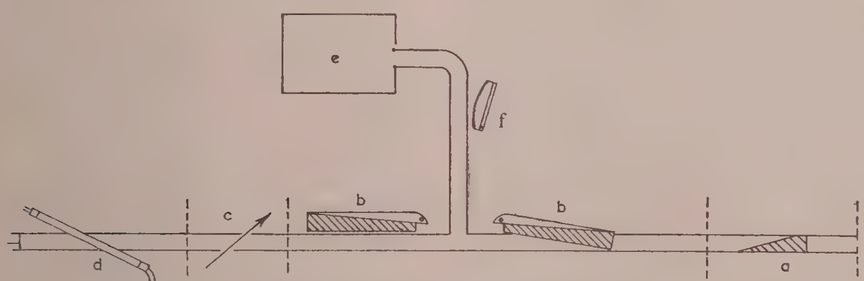

Fig. 1.—Arrangement for calibrating a secondary noise source.
(*a*) Hot primary source.
(*b*) Arm-blocking attenuators.
(*c*) Calibrated attenuator.
(*d*) Discharge-tube secondary source.
(*e*) Amplifier.
(*f*) Quarter-wave line stretcher.

The hot source, shown in more detail in Fig. 2, consists of a wedge of semi-conducting ceramic material lying at the centre of a 15 in length of fabricated-steel waveguide. The wedge presents an almost perfect match in the range from room temperature up to temperatures in the region of 600° C. The hot section is extremely well lagged by asbestos fibre and is heated by passing currents of up to 1 000 amp at 50 c/s through it lengthwise. Electrical connections for this heating current are made by bolting heavy copper strips to the steel waveguide. The capacity of the toroidal transformer shown in the drawing is such that power as high as 2 kW can be applied to the guide for rapid heating, although for continuous operation at 600° C only 400 watts is required. The water-cooling system is an essential feature, for without it the entire metallic structure would heat by conduction. Apart from the practical difficulties which would arise, the temperature of the arm-blocking attenuators would increase and confuse the interpretation of the experimental results. It was found necessary to interpose an extra water-cooled section of brass guide next to the hot source to give further protection.

The arm-blocking attenuators situated on each side of the

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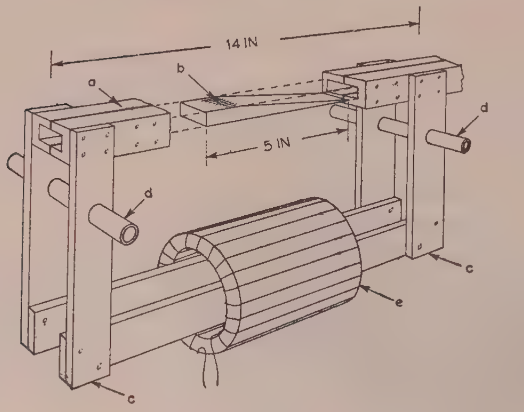

Fig. 2.—Hot source.

(*a*) Waveguide machined from mild steel in two sections and bolted together.
(*b*) Tapered slab of lossy material.
(*c*) Circuit of heavy copper strip.
(*d*) Tubes for cooling water.
(*e*) Iron core, toroidally wound.
The thick layer of asbestos-fibre lagging is not shown.

T-junction consist of 10 in long strips of 400-ohm resistance card. Each attenuator has two alternative positions into which it can be moved by an electromagnet. In the 'out' position the vane is entirely clear of the waveguide so that the temperature and impedance presented by the source to the T-junction are not affected. In the 'in' position the vane projects through a longitudinal slot in the broad face of the waveguide. The axis of rotation of the vane is such that the vane presents a tapered reflectionless termination of the T-junction. Attenuation of signals from the hot source is over 40 dB and so the arm temperature can be taken as being that of the resistance card. This differs from room temperature by less than one degree centigrade.

Noise from the two arms is mixed at the junction and amplified. The amplifier is a conventional X-band receiver with a type CV 129 local oscillator and a coaxial type of crystal mixer. The intermediate-frequency portion consists of a cascode triode section followed by three synchronously tuned pentode stages, giving a bandwidth of approximately 2 Mc/s centred at 14 Mc/s. The last stage feeds a germanium point-contact diode detector at a power level sufficiently low to give square-law rectification. As normally used, the rectified current is 5μA and is backed off by a steady current of the same magnitude. Any change of current, caused by a change of input noise power, is measured by a sensitive spot galvanometer. Changes in receiver gain can be troublesome, so care is taken to avoid drifts in gain caused by the heating of components. All power supplies are stabilized. At one stage during the experiment the available supply mains were subject to heavy intermittent local loads and it was found necessary to derive power from an alternator excited by a battery.

The effective temperature of the secondary source is higher than that of the primary source; the calibrated attenuator in the secondary-source arm was therefore arranged to be adjustable to make the effective temperatures in the two arms equal. When this is done there is no change of detector current as the arm-blocking attenuators change over, and the following relation holds:

$$\theta_{prim} = A\theta_{sec}$$

In this expression A is the attenuation in the calibrated attenuator expressed as a power ratio less than unity, and the source temperatures θ_{prim} and θ_{sec} are values in excess of room temperature. The expression is exact only when the calibrated attenuator and both arm-blocking attenuators are at room temperature, but variation from this condition is slight.

(3) POSSIBLE SOURCES OF ERROR AND EXPERIMENTAL PROCEDURE

A short calculation will show the order of magnitude of the quantities involved. Suppose the noise output power of the amplifier, when fed from a source at room temperature, is one unit. The amplifier contribution is $(N-1)/N$ units and the source contribution is $1/N$ units, where N is the noise factor of the amplifier.

Now let the temperature of one of the arms be θ deg C in excess of the room temperature T_r for which N has been specified. Then the output noise power is

$$(N-1)/N + \frac{1}{N}\frac{(2Tr+\theta)}{2Tr} \text{ units}$$

The factor 2 arises because in the experimental arrangement described here the effective temperature presented to the amplifier is derived equally from a hot source and an attenuating vane at room temperature. If $N = 10$, $\theta = 600°$ C and $T_r = 300°$ K the output noise power rises to 1·1 units.

Suppose now that it is desired to measure a temperature difference of one degree between the two arms. This is a reasonable aim, since the primary source temperature can be estimated to this order of accuracy. Then, as the arm-blocking attenuators change over, the amplifier output noise power changes by one part in 6000. This degree of accuracy could be realized by taking the mean of a sufficiently large number of readings (since there is no restriction on the time which may be taken in obtaining the result) were it not for the effect of systematic errors. These arise from a wide variety of causes and are worth detailed discussion.

An obvious source of error will be present if the arm-blocking attenuators are not at the same temperature. There is a tendency for the one on the primary side to heat because of conduction down the metal waveguide and by radiation from the warm outer surface of the lagging round the hot section. It was found necessary to interpose a water-cooled section to prevent conduction and a screen to reflect radiation. Another source of temperature difference is conduction from the windings of the electromagnets which operate the vanes. The effect was reduced to a fraction of a degree by introducing a light design of vane, with the weight almost balanced by a spring. The energizing power could then be reduced to less than 1 watt without sacrificing the speed of change-over.

The blocking attenuators can contribute another type of error. The moving parts impart a slight shock to the waveguide as they come to rest after change-over, a shock which is transmitted along the waveguide to the local oscillator and receiver and can cause coherent changes of gain. It was found that a heavy block of metal clamped to the section of guide leading to the receiver eliminated errors arising from this effect.

In discussing the next possible source of error it will be convenient to suppose the two arms to be identical in all respects as regards temperature and impedance, but that the primary arm blocking attenuator is slower in its operation than that in the secondary arm. During the change-over from primary to secondary connection there will be a brief instant when both sources are connected, and the effective temperature (excess over room temperature) will be twice that in the normal period between change-over times. During the reverse change, from secondary to primary connection, there will be an instant when both blocking attenuator vanes are in, and the effective temperature will be simply room temperature. Thus the output current of

ie detector, which should be constant, has alternate positive and gative pulses. In the language of a.c. waveforms, there is an nwanted signal in quadrature with the reference phase and any emodulator or phase-sensitive detector must be immune from is effect. In the simple detecting system which was used, amely a galvanometer reading noted by a human observer who so threw the change-over switch at regular intervals, it is neces-ry to operate at a frequency low enough to ensure that the eriod between changes is greater than the response time of the lvanometer. During the course of development of the experi-ent a variety of phase-sensitive demodulators and recording chniques were tried and discarded in favour of the simple ethod. The only concession to automation was a regular buzz om a loudspeaker which intimated the change-over time to the oserver.

It is well known that the noise factor and conversion gain of a icrowave receiver are dependent to a significant extent on the alue of the radio-frequency-source impedance. A systematic rror can thus arise if the two arms do not have identical impe-ances. An experimental estimate of the magnitude of this effect as made by connecting the amplifier to a length of waveguide ontaining a 6 dB attenuator and terminated by a short-circuit hose position could be varied. The source reflection coefficient as then 0·25, a value very much worse than that obtainable in e main experiment. The amplifier output power was plotted gainst the position of the short-circuit and the curve was a sine ave whose peak value was 0·025 times the mean output power. n the assumption that the deviations in output power are roportional to the magnitude of the r.f. source reflection coeffi-ient, an estimate can now be made of possible deviations in utput power due to the slight variations in source impedance hich may be encountered. It is found in practice that the arm npedances remain matched with a standing-wave ratio no orse than 1·05, but beyond this figure their constancy is unre-able. Early in this Section it was shown that a difference in mperature of one degree in the two arms corresponds to a hange in output power of one part in 6000. It is thus possible at an unlucky combination of impedances in the two arms ould give an apparent temperature difference of 15° C. This ould be the principal error in the experiment if no attempt were ade to cancel it. The effects of variation of source impedance n output power can, however, be made to reverse their sense by ngthening the waveguide to the amplifier by a quarter of a avelength. This was arranged by means of a dielectric flap noving into a slot in the broad face of the waveguide as illustrated Fig. 1. All measurements were made with the flap in and out, nd the average was taken of each pair of results. A satisfactory roof of the effectiveness of the quarter-wavelength flap, and ndeed of the apparatus as a whole, may be obtained by making a eries of measurements when both arms are known to be at the ame temperature, i.e. with nominally matched impedances at oom temperature in place of the primary and secondary sources. n one such series the results were as follows. With the flap out e amplifier output power changed by 0·003 60 as the arm-locking attenuators changed over. The figure is, of course, not single result but the average of a set of readings, taken in this ase at six-second intervals over a period of several minutes. Vith the flap in, the corresponding figure was 0·003 37, but was eversed in sense. Either figure alone would have indicated, roneously, a temperature difference of 20° C, but the average f the two corresponds to an error of only 0·7° C. It was found at errors of less than 1° could be obtained consistently.

One other type of systematic error remains to be discussed. he T-junction may not have perfect symmetry and so may ansfer power to the amplifier more effectively from one arm. his imperfection is not revealed in the test described above, since in that case the entire contents of both arms are at room temperature. However, the error arising from an unsymmetrical T-junction can be eliminated by reversing the connection of the arms to the T, or by reversing the T itself. Again, two sets of measurements must be made and the average taken.

(4) EFFECTIVE TEMPERATURE OF THE PRIMARY SOURCE

The effective temperature is determined by the following considerations. Let the source consist of a number of regions 1, 2, 3, . . . at temperatures θ_1, θ_2, θ_3, . . . in excess of room temperature. Now suppose an experiment to be performed in which power is fed to the source from an external generator, and that fractions of power P_1, P_2, P_3, . . . are absorbed in the various regions. Then the effective source temperature in excess of room temperature is given by

$$\theta_{eff} = \theta_1 P_1 + \theta_2 P_2 + \theta_3 P_3 + \dots$$

An exact assessment of θ_{eff} is a problem involving the temperature distribution and the field distribution of the incident test signal in three dimensions. Fortunately, as was shown by an exploring thermo-junction, the only significant temperature gradient here is lengthwise and transverse effects need not be considered.

The temperature distribution was obtained as follows. The temperature standard was a mercury-in-glass thermometer of high quality reading up to 360° C. The hot section of waveguide was used as a furnace in which four chromel-alumel thermocouples were calibrated against this standard. It was necessary to apply a stem correction for the glass thermometer, and to do this the shape of the temperature distribution along the stem was determined by one of the thermocouples. It was considered undesirable to have thermocouples inside the waveguide when the hot source was in use. Nor, in view of the large surface currents flowing to heat the waveguide, should thermo-junctions be in metallic contact with the outer surface. A satisfactory arrangement is to clamp the thermo-junctions at about a millimetre from the outer face, using asbestos clamps. The thermo-junctions lose heat to the lagging by radiation and record temperatures about 5° C lower than that of the corresponding point inside the guide. This temperature drop proved to be reliably constant when checked by means of an exploring thermo-junction inside the waveguide.

It is, of course, desirable that the waveguide temperature shall be not only measurable but constant over long periods of time. Automatic temperature control proved to be unnecessary since the supply voltage and cooling-water temperature had sufficient long-term stability. The power supply to the step-down transformer shown in Fig. 2 was fed from a variable-ratio transformer and an occasional readjustment was sufficient to maintain the source temperature within 1° C.

The arrangement of thermocouples established the temperature distribution along the hot source. In one case, for example, the temperature was 663° C at the centre of the wedge, falling to 592° C at the tip and rear. With a divergence of this magnitude an estimate of the power-loss distribution is clearly of some importance. Attempts to calculate this distribution from the known properties of the wedge material failed and an experimental method was resorted to. Two identical wedges were procured originally, and one of these was used in the calibration of the CV 1881. Then the two wedges were set back-to-back in a waveguide whose total attenuation could be measured. The attenuation through the pair was measured, first in their original state and then as half-inch lengths were removed progressively from their blunt ends. Two wedges are needed because a match must be maintained in such a measurement. An estimate of

P_1, P_2, etc., could then be made for the five one-inch sections of the wedge. The procedure can be criticized on the grounds that the field distribution in a section of the original complete wedge and in the same section in the cut-up form are not necessarily similar, but it seems unlikely that large errors will arise in a long tapered structure of the type used. A typical set of results is given in Table 1; the temperatures are those in excess of room

Table 1

Section No.	θ/θ_{max}	P	$P(\theta/\theta_{max})$
1	0·92	0·6	0·552
2	0·98	0·2	0·196
3	1·0	0·15	0·15
4	0·98	0·05	0·049
5	0·92	—	—

temperature. θ_{max} was 646° C; $\Sigma P(\theta/\theta_{max})$ was 0·947. Thus in this case the effective temperature at the tip of the wedge was estimated as 611° C.

A further factor affecting the effective temperature of the primary source as a whole is the small but not negligible attenuation in the steel waveguide between the tip of the wedge and the cool brass section. To measure this attenuation the wedge was removed and the heating power applied. A standing-wave measurement was made with the cool far end closed by a short-circuiting plate. No great difference was observed between the cold and hot readings of attenuation of the steel waveguide and so it was assumed that the attenuation when hot was almost uniform along the length despite the variation in temperature. A calculation showed that between the tip of the wedge and the cold loss-free brass guide a correction factor of 0·939 must be applied. This gave, in the example under consideration, a final value of 574° C for θ_{eff}, or 2·97 dB with respect to room temperature. After allowance for all possible sources of error it was estimated that there could be an error of not more than 10° or 0·08 dB in this result.

It would obviously be advantageous if a hot source could be constructed in which the lossy portion was at a uniform temperature. Several such sources were designed and built, but very steep temperature gradients are necessary and no model was so successful as the one described here.

The continuous use of room temperature as a reference level would be unjustifiable in a room where the temperature varied appreciably. The room used for the measurements, a basement, had a remarkably constant temperature; variation from 17° C rarely exceeded 2° C during the investigation.

(5) EFFECTIVE TEMPERATURE OF THE CV 1881 NOISE SOURCE

Fig. 3 shows the results of a series of measurements conducted with regard to the points mentioned in Section 3. Each point represents the average obtained for forty reversals of the arm-blocking attenuators. The final average value of the attenuator setting at which the two arms appear to have the same effective temperature is 12·54 dB. The primary-source effective temperature was 2·97 dB relative to room temperature. A correction of 0·3 dB must be made for the insertion loss and scale error of the calibrated attenuator. The result for the effective temperature of the gas-discharge tube is thus 15·81 dB relative to room temperature. The result is given to the nearest 0·01 dB, but it must not be assumed that the apparatus is capable of producing this degree of accuracy. The experiment was performed three times, the apparatus being dismantled and reassembled after each measurement, and the results were: 15·81, 15·73 and 15·72, average 15·75 dB.

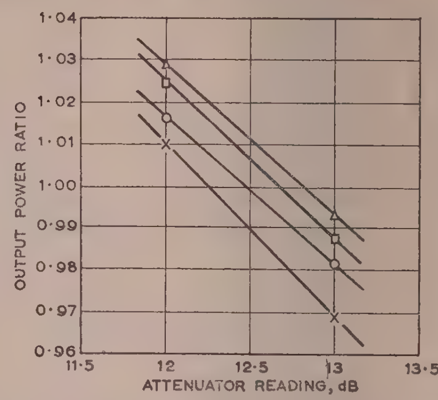

Fig. 3.—Experimental results for a CV 1881 discharge tube.

△ Line stretcher in, T-junction normal.
□ Line stretcher out, T-junction normal.
○ Line stretcher in, T-junction reversed.
× Line stretcher out, T-junction reversed.
Primary source temperature in excess of room temperature was +2·97 dB.

It is believed that the principal reason for the spread of about 0·1 dB in the results was the variability of the particular calibrated attenuator used. The instrument was calibrated against an intermediate-frequency attenuator after each measurement, this indeed being the reason for dismantling the equipment. The resetting accuracy, including the effects of assembly into a waveguide testing circuit, was not reliable to better than 0·1 dB, nor was it thought that the calibrating technique was reliable to better than 0·1 dB.

(6) CONCLUSIONS

A hot source has proved to be a reasonably consistent power standard in the 3-cm band. Such a source has been used to measure the effective temperature of a secondary standard noise source, the gas-discharge tube CV 1881. The result was 15·75 dB excess with respect to room temperature, with a possible error of not more than 0·3 dB. This result is in good agreement with results which have been obtained by the conventional sinusoidal-signal generator method.

(7) ACKNOWLEDGMENTS

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DISCUSSION ON 'MAINTENANCE PRINCIPLES FOR AUTOMATIC TELEPHONE EXCHANGE PLANT'*

Before the North Staffordshire Sub-Centre *at* Stone *15th November, the* Southern Centre *at* Portsmouth *7th December*, 1955, *and the* North-Eastern Radio and Measurements Group *at* Newcastle upon Tyne *5th March*, 1956.

Mr. H. Baker (*at Stone*): The paper can be considered as a brief summary of the development of a new maintenance philosophy that has been gradually emerging over the years, but as such I consider that insufficient stress has been placed on the responsibilities that should be carried by the equipment and circuit designers for a satisfactory maintenance performance.

It is unfortunate that Fig. 6 suggests an approximately linear relationship between wear and time, for it should show a rapid initial change after an adjustment, followed by a relatively long period of fairly stable performance (this includes the variations caused by temperature, humidity, etc.) and finally a rapid deterioration as the various parts wear and aggravate each other. Thus, unless the initial bedding-down and the fortuitous variations are included in the design stage as acceptable tolerances, an impracticable and costly maintenance technique must be evolved to keep the equipment within limits that are inherently too tight.

This same approach to maintenance can with advantage be applied to electronic equipment. The Post Office has been conducting an experiment in which six electronic register translators were installed at a London telephone exchange and have been giving 24-hour service for the last four years. When designing this equipment it was decided that the early recognition of plant faults and the busying-out of that piece of equipment to prevent service faults was a most suitable approach to its maintenance. Early recognition in this first experimental equipment was achieved with functional testers to give an overall picture, together with in-built monitoring devices to watch common pulse or power supplies, etc., and to give automatic busying. With the full co-operation of the local maintenance staff, each fault was located and verified before correction, and an analysis of the faults shows two significant characteristics. First, that most of the faults were catastrophic by nature (disconnected or short-circuited wires, heaters, resistors, etc.), so rendering preventive maintenance unsuitable. Secondly, on the average, over half the faults on each piece of equipment occurred within a week of a preceding fault, although an average frequency of fault occurrence was one every two or three months, indicating that interference caused or triggered off faults, thus increasing the fault rate.

Various other techniques that also show promise in helping to solve the maintenance problem for future designs take advantage of the flexibility and very high speed of operation of electronic equipment and can exploit the advantages indicated by the theory of probability, whereby if the probability of a casual event is 1 in n, the probability of its occurring twice is 1 in n^2. These can be incorporated economically so long as they are introduced at the design stage.

One idea is to run three common translators in parallel (rather than each taking a part load), and so long as any two give the same answer, it is accepted by the registers. This arrangement can give either a greatly improved grade of service compared with a single translator, or if the same overall grade of service is acceptable, it will allow the individual translators to be greatly simplified and cheapened, since the three translators become self-checking, and the individual internal self-checking features which would otherwise be required are unnecessary; equally, no overall monitor is required. This feature is also self-correcting, since the quality of service is safeguarded even when one of the translators in an unattended exchange is faulty.

A second practicable proposal is to monitor a call while it is being set up, and if the subscriber is left with an implausible call (e.g. 'no tone') or a poor transmission path, a failure is recorded and the call is set up again rapidly over another path. This would not only give an overall check of the exchange, but would also give service to the subscribers under conditions of partial failure of some item within a piece of common equipment that could not in itself be busied out of service.

Mr. C. F. Bougourd (*at Portsmouth*): The Post Office has made big changes in maintenance procedure: 30 years ago it was the rule to test each selector functionally each day, but now it is done twice a year; other routines and overhauls have been similarly reduced.

As a result of admittedly limited trials, we in the Portsmouth Area have decided to overhaul switches at a 4-year interval, and to give full power to the technical officer in charge to use his

* Palmer, R. W.: Paper No. 1777, January, 1955 (102 B, p. 453).

discretion as to the amount of work required, so that busy switches can be thoroughly overhauled if required and lightly loaded switches can merely be thoroughly cleaned and lubricated. What is the present position regarding national policy?

On the question of design, is anything being done to end the prevalence of double connections, since this causes more trouble and suspicion than any other fault? Also, is any work being carried out to provide self-testing and self-busying on faulty circuits, as used in the telegraph automatic switching scheme? I realize that economics must enter into this, but suggest that, unless some such improvement is made, the reduction in maintenance effort which can be achieved will be limited.

Mr. J. Queen (*at Newcastle upon Tyne*): If the 'work unit' must not be used as a yardstick in determining the staff needed to maintain an automatic telephone exchange, what other means has the engineer for this purpose? In general practice the preventive maintenance scheme seems wasteful of manpower and the contrary may be said of the corrective arrangement, which is limited in its application. Qualitative maintenance as a combination of preventive and corrective maintenance appears to meet the general case. Are there weighting factors available which would enable one to determine approximately the staff needed in any particular instance?

In maintenance investigations difficulty is experienced in finding a generally accepted definition for the term 'fault'. The difficulty arises when service complaints are found to be due to a combination of causes. In my opinion a distinction should be made, a service interruption due to a single cause being a 'simple' fault and one due to a number of causes being a 'compound' fault.

Service complaints arise from the effects of oxidation of contacts which are part of junction relay set speech-transmission circuit. The oxidized contacts cause circuit unbalance and consequent complaints of noise. So far as I am aware, routiners do not check this aspect of automatic exchange equipment. Is there likely to be any development in design of routiners to cover this aspect of circuit operation?

Experience has shown that, when relay-set components are assembled or replaced, care in positioning of them receives little special attention; thus the voice-frequency balance of automatic equipment is neglected. Closer liaison between the switching and the transmission engineers is necessary. For maintenance and the assembly of circuits, some form of jig should be used to fix the correct position of relays connected to the junction speech-transmission circuit in respect to other relays. This would improve the control of leakage flux of adjacent relays on the v.f. impedance balance of the relay sets. Is there any development in this direction?

Mr. F. A. Copley (*at Newcastle upon Tyne*): As an aid to maintenance of telephone exchanges, will the author give his opinion on the design of telephone areas? The present design of exchanges in the Newcastle Area is anything but an aid to maintenance, since five different types are at present in existence and this does not assist in staffing problems. The various types are

(*a*) Non-director.
(*b*) Discriminator repeater (satellite).
(*c*) Satellite first selector with discriminator.
(*d*) Line-finder.
(*e*) Modified discriminator repeater with additional discriminator.

If all exchanges were of the non-director (group-selector) type, this would simplify the system and be a definite aid to maintenance.

A further point on design is that of the automatic routiner for automatic-to-automatic relay sets. The present routiner caters for one train of impulses per test cycle. This is insufficient to give an adequate test on the regenerator incorporated in the relay set under test. I suggest that two or three trains of impulses be provided per test, thereby improving the usefulness of the routiner.

Mr. W. Brittlebank (*at Newcastle upon Tyne*): As mentioned in Section 4, the accumulation of dust is an important problem in apparatus rooms. In supervisory equipment, which is of a very similar nature, dust-tight covers have been employed with much success. Does the author consider that suitable covers on the switches and selector banks might be beneficial?

Mr. A. E. Twycross (*at Newcastle upon Tyne*): The Post Office commercial accounts indicate that the maintenance of telephone plant absorbs some 20% of the total telephone income, and since the telephone is in the nature of an overhead charge on industry, avoidance of wasted effort is of paramount importance, particularly as the system is expected to double itself during the next 20 years. The paper is therefore very timely in showing the possible ways in which the same quality of service may be maintained at less overall cost.

As a local experiment, a shelf of final selectors was sealed off in a particular exchange and no attention was given beyond lubrication. After three years some interrupter spring trouble developed; this was rectified and the shelf has given a further 12 months' fault-free service.

Mr. R. W. Palmer (*in reply*): In answer to the many questions on equipment design, such as were asked by Messrs. Bougourd, Copley and Queen, I can only draw attention to the age-old conflict between stability and progress in its relation to maintenance efficiency. The point has already been made that initial design should take account of maintenance needs, but the introduction of successive improvements in design is bound to create the difficult situation where half a dozen different vintages have to be maintained side by side. To apply all improvements retrospectively to old plant is usually impracticable. One wonders whether the United States administration was right in resisting changes to their old Strowger system, even to the retention of single-contact relays.

Mr. Twycross adds to the fund of experience supporting the policy of minimum preventive maintenance. The frequency of overhauls is already being reduced gradually in the British system, with due regard to the needs of individual switches. I accept the criticism that Fig. 6 is an over-simplification of the way in which wear develops, but this was done deliberately to focus attention on test and acceptance tolerances. The initial bedding-down process deserves the production of a separate graph which should be based on precise laboratory experiments. As for Mr. Brittlebank's question on dust covers, the protection of selector banks might be worth while if a cheap cover could be produced, and the Post Office Engineering Department would be pleased to have details of any experience with such covers on supervisory equipment.

Many suggestions have been made to add more and more test facilities, but they are not necessarily suitable for *routine* testing. I favour the incorporation of self-testing facilities in the operational sense, leaving detailed testing to be done on a qualitative principle. Under such conditions the determination of staff requirements is more difficult than when routine maintenance is rigidly scheduled, but my answer to Mr. Queen is that 'work units' can still be used as a guide to initial staffing. The man-hours per work unit should be adjusted as the frequency of trouble is reduced by skilful maintenance attention.

The contribution by Mr. Baker on the maintenance possibilities in electronic switching equipment provides a fitting climax to this review of maintenance principles. The new developments clearly call for a drastic change in the pattern of maintenance effort, and it is as well to have an eye to the future while discussing the problems of to-day.

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DEVELOPMENT OF THE COLLARD PRINCIPLE OF ARTICULATION CALCULATION

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SUMMARY

Many rather laborious talker–listener assessments of speech links ›uld be avoided if the theoretical framework propounded in 1929 by ›llard were more generally applied. This theory permits the articula- ›n score to be calculated, given the frequency characteristics, noise ›el and transmission losses of any telephone circuit. The paper ›presses this principle in terms of a simple mathematical model ›fined by a very few parameters which have been estimated from ›cent measurements made by the Post Office.

The practical application of these results to the calculation of ›ticulation can be reduced to a convenient procedure which is ›scribed in an appendix and illustrated with some numerical examples.

Measurements and calculations based on the theory agree under ›vourable conditions to within a few per cent of sound articulation; ›hen commercial subscribers' sets are involved, however, a careful ›oice must be made of the method of measuring the sensitivity/fre- ›ency characteristics of the transducers.

Although actual articulation measurements cannot yet be com- ›etely dispensed with, the calculation technique does enable a large ›nount of information to be interpolated from a relatively small ›umber of measurements on key conditions.

LIST OF PRINCIPAL SYMBOLS

f = Frequency, c/s.

s = Sound articulation as a proportion, $0 \leqslant s \leqslant 1$.

s_{Li} = Sound articulation obtained with a channel having a low-pass filter with cut-off at f_i.

s_{Hi} = Sound articulation obtained with a channel having a high-pass filter with cut-off at f_i.

s_{Hj} = Sound articulation obtained with a channel having a high-pass filter with a cut-off at f_j in addition to a low-pass filter with cut-off f_i. ($f_j < f_i$.)

S = Speech power, watts.

N = Noise power, watts.

x = Speech/noise ratio expressed in dB; also used for the setting of an attenuator during an articulation measurement.

$x_{0\cdot 8}$ = Setting of an attenuator corresponding to $s = 0\cdot 8$.

B = Maximum possible value of band articulation with a low-pass filter in circuit, $0 \leqslant B \leqslant 1$.

B' = Derivative of B with respect to f, or band-articulation weighting coefficient.

P = Proportion of maximum possible contribution to band articulation of a narrow frequency band, $0 \leqslant \mathrm{P} \leqslant 1$.

$l(\mathrm{P})$ = 'Logit' of P, defined as arc tanh $(2\mathrm{P} - 1)$.

$\overline{\mathrm{P}}$ = Band articulation, or weighted mean of P.

$w(f)$ = Function relating B' to f; $B' = w(f)$.

$\phi(\overline{\mathrm{P}})$ = Function relating s to $\overline{\mathrm{P}}$; $s = \phi(\overline{\mathrm{P}})$.

$\psi(S/N)$ = Function relating P to S/N; $\mathrm{P} = \psi(S/N)$.

$_1, a_2, b_1, b_2$ = Parameters of ϕ and ψ.

(1) INTRODUCTION

The proportion of words or syllables correctly received over a telephone channel has been used for many years as a measure of the effectiveness of that channel for transmitting speech. The earliest reference is by Campbell[1] in 1910, but records of such articulation measurements by the British Post Office date back at least to 1905.

It is clearly desirable to be able not only to measure the performance of any given speech link but to relate this to its physical characteristics. This was first attempted by Collard in 1929.[2, 3, 4] Further work based on Collard's theoretical approach has been published by Pocock,[7] French and Steinberg,[11] and Beranek.[12] An alternative basis has more recently been suggested by Fletcher and Galt.[15] Much use has been made in the Post Office of calculations based on the Collard theory, including an extensive study[5] during 1934–36, in co-operation with the C.C.I.F. Laboratory (then the S.F.E.R.T. Laboratory), of the possible application of the theory to international telephone assessment problems. An elegant theorem by Ackroyd,[14] also based on this theory, was used to predict the best frequency characteristics for hearing aids and telephone transmitters.

Improvements since 1946 in the technique of conducting articulation measurements[19] and of analysing the results, coupled with the use of a high-quality reference telephone channel,[16] now enable the Collard theory to be set in a new mathematical framework.

Two purposes for developing an articulation calculation technique must be clearly distinguished. One purpose is the very practical one of dispensing with actual measurements, to save time and expense. Another would be to express the performance of a telephone channel in terms which are independent of the actual articulation-testing crew, i.e. in terms of an ideal articulation score. The method described here has only the first purpose in view. The technique attempts to reproduce by calculation the results which would be obtained by one particular crew trained in a given manner and following a closely specified procedure. The information given here should enable a more rational approach to be made to many telephone design problems which are at present studied by means of series of articulation measurements.

The sequence adopted is as follows:

(*a*) To elaborate the theoretical framework.

(*b*) To discuss measurements made by means of a high-quality telephone channel from which the parameters of the basic data are deduced.

(*c*) To consider very briefly the application to commercial telephone channels.

(2) THEORY

The Collard theory is based on the following statements:

(i) The syllable or sound articulation as measured is uniquely related to a quantity termed 'band articulation'.

(ii) The band articulation is the weighted mean over the speech frequency range of a quantity P which is a function of speech-to-threshold (or speech-to-noise) ratio. The weighting function is fundamental and is a function only of frequency.

Written contributions on papers published without being read at meetings are ›vited for consideration with a view to publication.

Mr. Richards and Mr. Archbold are at the Post Office Research Station.

Statement (ii) may be written

$$\overline{P} = \int B'P df$$

where $\overline{P}$ is the band articulation, B' is the frequency weighting function and is the derivative with respect to frequency of a quantity B which will be referred to later, and P is a function of S/N. S is the speech power at the ear and N is the noise power at the ear. The ratio S/N is also a function of frequency, depending on the telephone channel. It will be necessary to consider $B = \int_0^{f_i} B' df$ as a function of f_i, i.e. the cumulated value of B'. The quantities $\overline{P}$ and P are analogous to probabilities and, like B, range from 0 to 1.

Sound articulation (which is used here in preference to syllable articulation) is related to band articulation by a single-valued function $s = \phi(\overline{P})$.

Writing B' and P as $w(f)$ and $\psi(S/N)$ the complete hypothesis becomes

$$s = \phi\left[\int_0^\infty w(f)\psi(S/N)df\right] \quad . \quad . \quad . \quad . \quad (1)$$

The problem then becomes one of determining ϕ, w and ψ so that best agreement is secured between measurement and calculation. As might be expected, considerable flexibility is possible in the forms of these functions. It is therefore attractive to seek simple mathematical forms for them which can be specified by not more than, say, two parameters each. To estimate these parameters will, of course, be a simpler process than estimating a curve of unrestricted form.

Success has been achieved over several years in using the logistic curve for fitting to sound-articulation/sensitivity measurements; a technique for analysing the results of articulation measurements based on a logistic transformation and applying the polynomial coefficient method (Emmens)[13] has been developed in the Post Office and has been adopted by the C.C.I.F. Laboratory.[17, 22] Moreover, P as a function of $10 \log_{10}(S/N)$ is also a sigmoid of approximately symmetrical form, and so the logistic function seemed a reasonable choice for this function as well. A possible theoretical justification for the logistic function in this context is given elsewhere.[25] Accepting the two logistic functions for s and P defines the form of relation between s and $\overline{P}$.

The most convenient form of the logistic function is

$$f(x) = \tfrac{1}{2} + \tfrac{1}{2}\tanh(a + bx)$$

where a and b are parameters and $x = 10 \log_{10}(S/N)$, namely the speech/noise ratio of the telephone channel in decibels or the sensation level at the ear of the listener. (Sensation level is the level of a sound above the threshold of audibility masked by any noise reaching the ear.)

If S/N is independent of f, eqn. (1) may be written

$$s = \phi\left[\int_0^\infty w(f)df\psi(S/N)\right] \quad . \quad . \quad . \quad . \quad (2)$$

But, by definition, $\int_0^\infty w(f)df = 1$. Therefore, under these conditions, $s = \phi[\psi(S/N)]$.

We may substitute $P = f_1(x)$ for $\psi(S/N)$ so that decibels may be used rather than ratios of speech-power to noise-power. Then

$$P = f_1(x) = \tfrac{1}{2} + \tfrac{1}{2}\tanh(a_1 + b_1x) \quad . \quad . \quad . \quad (3)$$

and

$$s = f_2(x) = \tfrac{1}{2} + \tfrac{1}{2}\tanh(a_2 + b_2x) \quad . \quad . \quad . \quad (4)$$

from which

$$s = \phi[\tfrac{1}{2} + \tfrac{1}{2}\tanh(a_1 + b_1x)]$$
$$= \tfrac{1}{2} + \tfrac{1}{2}\tanh(a_2 + b_2x)$$

Writing

$$Y_1 = a_1 + b_1x \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and

$$Y_2 = a_2 + b_2x \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and using the inverse functions

$$Y_1 = \text{arc tanh}\,(2P - 1)$$

and

$$Y_2 = \text{arc tanh}\,(2s - 1)$$

we have

$$Y_1 = a_1 + (b_1/b_2)(Y_2 - a_2)$$

and

$$\text{arc tanh}\,(2P - 1) = a_1 + (b_1/b_2)[\text{arc tanh}\,(2s - 1) - a_2] \quad . \quad (7)$$

This will simplify, if desired, by substituting

$$\tfrac{1}{2}\log_e[P/(1 - P)] = \text{arc tanh}\,(2P - 1)$$

to give

$$P/(1 - P) = [\exp(2a_1 - 2a_2b_1/b_2)][s/(1 - s)]^{b_1/b_2} \quad . \quad (8)$$

Because arc tanh (2P − 1) has been tabulated as a function of P (see, for example, Finney[20]) the most convenient form is

$$\text{arc tanh}\,(2P - 1) - a_1 = (b_1/b_2)[\text{arc tanh}\,(2s - 1) - a_2] \quad . \quad (9)$$

arc tanh (2P − 1) is termed the 'logit' of P* and will be denoted by $l(P)$.

Therefore

$$l(P) - a_1 = (b_1/b_2)[l(s) - a_2]$$

or

$$l(s) - a_2 = (b_2/b_1)[l(P) - a_1]. \quad . \quad . \quad . \quad (10)$$

which gives the required form of the function $s = \phi(P)$. The same function applies for $s = \phi(\overline{P})$ in the general case when P is not constant.

The function $P = f_1(x)$ may be written either in the form of eqn. (3) or in the form

$$P = 1/\{1 + \exp[-2(a_1 + b_1x)]\} \quad . \quad . \quad . \quad (11)$$

whence, substituting $x = 10 \log_{10}(S/N)$

$$P = 1/\{1 + [\exp(-2a_1)](S/N)^{-b_1/0 \cdot 1151}\} \quad . \quad . \quad (12)$$

If a_1 and b_1 assume the critical values 0 and 0·1151 respectively, we have $P/(1 - P) = S/N$. In fact, as will be seen later, these critical values are not found, although the departure is not very great.

Of the three functions ϕ, w and ψ which appear in eqn. (1), ϕ is defined by eqn. (10) and ψ by eqn. (12). Functions ϕ and ψ are defined, therefore, by the four parameters a_1, a_2, b_1 and b_2. Estimation of these and determination of the function w will be described below.

(3) ESTIMATION OF PARAMETERS

The parameters a_1, a_2, b_1 and b_2 are estimated from the results of a series of articulation measurements using a high-quality telephone channel in which, not only is the precise frequency bandwidth known, but also the value of S/N can be set to a number of controlled values. To a considerable extent the estimation of the parameters of all three functions ϕ, ψ and w proceeds simultaneously.

The high-quality telephone channel used has been described elsewhere;[16] the sensitivities of the sending and receiving ends

* The logit of P is more frequently defined as 5 + arc tanh (2P − 1) so as to avoid negative numbers in most practical cases. Omission of the additional 5 is more convenient in the present discussion.

e given in tabular form in Table 13 (Section 9). The sending ıd receiving ends are connected together by a variable attenuator 600 ohms characteristic impedance with which may be sociated a filter or other transmission element. A speech ›ltmeter is bridged across the output terminals of the sending ıd so that the speech level may be controlled.

The material used consists of lists of logatoms (consonant– ›wel–consonant combinations) each based on the strongly ressed syllables of English conversational speech.[23]

(3.1) Determination of the Parameters of ϕ

The first set of measurements is conducted with the aid of a t of filters with the ratio S/N large enough to ensure that all equency components transmitted within the pass range con- ibute their maximum to the band articulation. Outside the ass range the attenuation must be so great that no contribution made. In other words, P = 1 in the pass range and P = 0 utside. The filters actually used here attenuated at least 60 dB › within 9% of the cut-off frequency.

Measurements were made using complementary low-pass and igh-pass filters with cut-off at $f_1, f_2, f_3, \ldots f_n$ (n should be not ss than 5 and the frequencies should range from approximately 00 to 4 000 c/s). By ensuring that the sensitivity of each channel set to yield the maximum value of sound articulation, the con- ition P = 1 in the pass range is ensured. Except at very low equencies of low-pass filter and very high frequencies of high- ass filter, the maximum value of articulation occurs within the ange ±10 dB about the sensitivity corresponding to a one-metre ir path, namely 30 dB attenuation between sending and receiving nds of the high-quality channel employed. It was therefore ufficient to measure at the three settings of 20, 30 and 40 dB nd to take the mean values of sound articulation. The results f these measurements are as follows, and will be referred to as set of complementary sound articulation values and denoted y s_{Li} and s_{Hi} for the frequency f_i.

Table 1

Complementary Sound-Articulation Values

Frequency	Measured sound articulation	
	Low-pass filter	High-pass filter
c/s	%	%
600	65·5	98·7
850	75·7	98·3
1 200	84·5	95·8
1 700	90·4	91·9
2 400	96·3	81·0
3 400	97·9	72·5

For the channel used in measuring s_{Li}

$$\psi(S/N) = 1 \qquad 0 \leqslant f \leqslant f_i$$
$$\psi(S/N) = 0 \qquad f_i < f$$

nd when s_{Hi} was measured

$$\psi(S/N) = 0 \qquad 0 \leqslant f \leqslant f_i$$
$$\psi(S/N) = 1 \qquad f_i < f$$

herefore $$s_{Li} = \phi\left(\int_0^{f_i} B'df\right)$$

nd $$s_{Hi} = \phi\left(\int_{f_i}^{\infty} B'df\right)$$

Let $$B_i = \int_0^{f_i} B'df$$

then $$1 - B_i = \int_{f_i}^{\infty} B'df$$

because $$\int_0^{\infty} B'df = 1$$

Therefore $$s_{Li} = \phi(B_i) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$s_{Hi} = \phi(1 - B_i) \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The logistic is an odd function of $\overline{\mathrm{P}} - \frac{1}{2}$ and therefore

$$l(1 - \overline{\mathrm{P}}) = -l(\overline{\mathrm{P}})$$

And, for these filtered channels, $\overline{\mathrm{P}} = B$.

From eqns. (10), (13) and (14)

$$l(s_{Li}) - a_2 = (b_2/b_1)[l(B_i) - a_1] \quad . \quad . \quad . \quad (15)$$

and $$l(s_{Hi}) - a_2 = (b_2/b_1)[-l(B_i) - a_1] \quad . \quad . \quad . \quad (16)$$

Adding eqns. (15) and (16),

$$l(s_{Li}) + l(s_{Hi}) - 2a_2 = -2(b_2/b_1)a_1$$

Therefore $$l(s_{Li}) + l(s_{Hi}) = 2a_2 - 2a_1(b_2/b_1)$$

When $$B_i = 0{\cdot}5,\ l(s_{Li}) = l(s_{Hi})$$

let the corresponding value of s be $s_{0\cdot5}$.

Therefore $$l(s_{0\cdot5}) = a_2 - a_1(b_2/b_1) \quad . \quad . \quad . \quad . \quad (17)$$

If $l(s_{Hi})$ is plotted against $l(s_{Li})$ the result should be a straight line of slope −1 passing through 0, $(2a_2 - 2a_1b_2/b_1)$. Where this line intersects the line $l(s_{Li}) = l(s_{Hi})$, B_i is 0·5, whence we have the value of $l(s_{0\cdot5})$ and therefore of $s_{0\cdot5}$.

The test of the foregoing is whether a straight line of slope −1 is in fact obtained. The data of French and Steinberg,[11] Fletcher and Galt,[15] and of two previous unpublished Post Office determinations carried out in 1935 using different types of logatoms from those now employed, have been plotted in this way and show reasonable agreement with this hypothesis. The

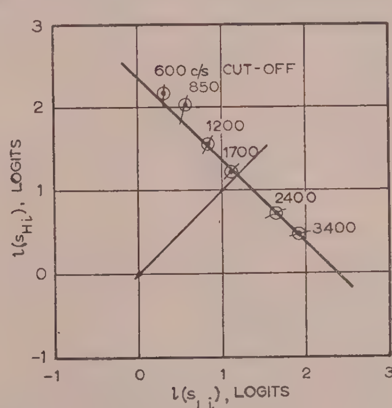

Fig. 1.—Relation between complementary sound-articulation values expressed as logits.

data given in Table 1 have been plotted in Fig. 1. The agreement is typical of that obtained using any of the other data, but, as might be expected from the use of different logatoms and

measuring techniques, the value of $(2a_2 - 2a_1b_2/b_1)$ varies as follows:

From data in Table 1(Fig. 1)	2·36 (91·4%)
French and Steinberg	1·90 (87·0%)
Fletcher and Galt	1·92 (87·2%)
Post Office (1935):	
With Esperanto logatoms..	2·00 (88·1%)
With earlier type of English logatoms ..	1·76 (85·3%)

The figures in brackets are the corresponding values of $s_{0\cdot5}$; these have been obtained from eqn. (17).

If one more value of s can be determined for a known value of $\bar{P}$, the function ϕ can be defined. It is convenient to determine $s_{0\cdot25}$, which may be done in either of two ways.

The preferred method is that described in the original paper by Collard and is as follows. The value of $s_{0\cdot5}$ having been determined, the corresponding cut-off frequency of a low-pass filter can be estimated from the measurements; let this be $f_{0\cdot5}$. Using such a low-pass filter, a further set of measurements must be made using also a set of high-pass filters whose cut-off frequency is less than $f_{0\cdot5}$. The articulation value at which s_{Hj} in this new set of measurements equals s_{Li} of the previous set yields $s_{0\cdot25}$. The method is equally applicable using a high-pass filter with cut-off at $f_{0\cdot5}$ together with a set of low-pass filters. The disadvantage of this method is that a special high-grade filter must be made after the first set of measurements have yielded $f_{0\cdot5}$. Suitable filters are very expensive and usually take a long time to produce.

The method used here is that described by French and Steinberg. A channel of unrestricted bandwidth is attenuated in sensitivity until s falls to $s_{0\cdot5}$. The low-pass and high-pass filters used previously are then inserted and a new set of articulation measurements made; let these results be denoted by s'_{Li} and s'_{Hi}. It is then argued that, when $s'_{Li} = s'_{Hi}$, $\bar{P} = 0\cdot25$. This method has the disadvantage that, under the attenuated channel conditions, P is not constant within the pass range of the filters. This does not invalidate the determination of $s_{0\cdot25}$, but the frequency at which $s'_{Li} = s'_{Hi}$ is not necessarily the same as $f_{0\cdot5}$. This feature could be overcome by degrading the channel with noise of such spectrum that P was constant within the pass range of the filters instead of attenuating the channel.

These results yield $s_{0\cdot25} = 65\%$. Therefore, because $s_{0\cdot5}$ has already been estimated at 91·4%, $l(s_{0\cdot5}) = 1\cdot18$ corresponds to $l(\mathrm{P}) = l(0\cdot5) = 0$, and $l(s_{0\cdot25}) = 0\cdot31$ corresponds to $l(\mathrm{P}) = l(0\cdot25) = -0\cdot55$.

From eqn. (10)

$$1\cdot18 - a_2 = (b_2/b_1)(-a_1)$$

$$0\cdot31 - a_2 = (b_2/b_1)(-0\cdot55 - a_1)$$

from which $$b_2/b_1 = 1\cdot58 \quad (18)$$

and $$(a_2 - a_1b_2/b_1) = 1\cdot18 \quad (19)$$

Therefore $$l(s) = 1\cdot18 + 1\cdot58l(\bar{\mathrm{P}}) \quad (20)$$

which is the required function ϕ.

This has been plotted in Fig. 2 on percentage scales.

(3.2) Determination of the Parameters of ψ

The foregoing yields $(a_2 - a_1b_2/b_1)$ and b_2/b_1, but the required parameters of P as a function of x are a_1 and b_1 [eqn. (3)].

The experimental data now required are s as a function of x under conditions where P is constant, i.e. with $\mathrm{P} = \bar{\mathrm{P}}$. The values of s can then be transformed to values of $\bar{\mathrm{P}}$ by eqn. (20) or Fig. 2. This condition can most conveniently be met by

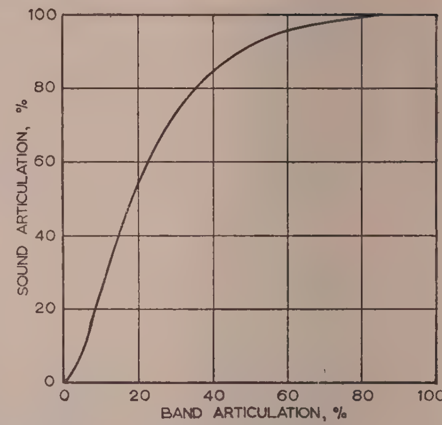

Fig. 2.—Sound articulation as a function of band articulation. (Function ϕ.)

degrading the channel with random noise which has the same power-density spectrum as that of the speech, and choosing the listening level so that the threshold of audibility is completely masked by the noise at all speech frequencies; this ensures that x is independent of frequency and that P is therefore constant. a_2 and b_2 can then be estimated from the data by fitting eqn. (4) by the method of maximum likelihood.[20]

The spectrum of speech given by Ackroyd[14] has been found to be in good agreement with later Post Office determinations and so the mean of those results for male and female speakers has been taken. (The Post Office articulation crew is composed equally of males and females.) An equalizer has been constructed having this frequency characteristic, and white noise has been shaped by transmitting it through this equalizer.

At this stage it is necessary to consider the definition of units in which x is to be measured. An arbitrary choice must be made of the method of measuring the levels of the speech and the noise. An obvious choice for measuring noise of random character is to measure its mean power or the r.m.s. value of the noise voltage. It is possible also to use mean power for speech, and indeed this was done by French and Steinberg and by Fletcher and Galt. Pocock has followed Collard in using peak values. The problem of measuring speech levels is discussed by Shearme and Richards,[28] and it is sufficient to state that speech levels have here been measured with a speech voltmeter. When logatoms are spoken by members of a trained articulation crew the speech voltage exceeds the r.m.s. value by 1·4 dB. The corresponding relation for continuously spoken speech (read from a book) is 6·9 dB. The r.m.s. value is difficult to measure during conversation owing to the fragmentary nature of the speech; speech voltage, however, is equally applicable to all types of speech, although its relation to other measurements may differ.

It is pointed out by French and Steinberg that the distribution (on a decibel scale relative to a given percentile) of speech levels within narrow frequency bands is practically independent of frequency; it follows that a constant difference exists between any two percentiles. It is therefore permissible to choose the speech spectrum level in such a way that when integrated the speech voltage is given, and to regard the result as applying to the same percentile for narrow frequency bands as the speech voltage does for whole-band speech. The speech pressure at 13¼ in from the lips for reference vocal level is 1 dyne/cm², and so (assuming the shape of spectrum already referred to) the power-density spectrum expressed relative to the power corresponding to 0·0002 dyne/cm² in a 1 c/s bandwidth at this point is as given in Table 2.

Table 2

Miscellaneous Basic Data

Band number	Mid-frequency	Speech spectrum		Spectrum of typical room noise		Threshold of audibility
		1 dyne/ cm^2	11 dynes/ cm^2	50 dB level	60 dB level	
	c/s	dB	dB	dB	dB	dB
1	98	40	61	33	41	19
2	236	46	67	27	35	3
3	372	47	68	24	32	−2
4	510	46	67	22	30	−6
5	646	42	63	20	28	−10
6	784	39	60	18	26	−12
7	926	36	57	18	26	−14
8	1 083	34	55	16	24	−14
9	1 272	32	53	15	23	−13
10	1 493	30	51	14	22	−12
11	1 752	28	49	13	21	−11
12	2 055	27	48	12	20	−11
13	2 411	26	47	10	18	−13
14	2 830	24	45	9	17	−10
15	3 319	22	43	8	16	−8
16	3 894	19	40	6	14	−7
17	4 570	16	37	4	12	−9
18	5 363	15	36	2	10	−9
19	6 293	14	35	−1	7	−5
20	7 385	13	34	−4	4	−3

The above are referred to a datum of 0·0002 dyne/cm² in a 1 c/s bandwidth.
Room noise level is specified in terms of the reading of a sound-level meter. Different requency weightings are used for levels below and above 55 dB.

The values of a_2 and b_2 obtained on this basis are 1·99 and ·135 respectively. Hence a_1 and b_1 can be calculated from qns. (18) and (19) ($a_1 = 0·513$, $b_1 = 0·0855$). Substituting a_1 and b_1 in eqn. (12) yields the function ψ. In practice it is more convenient to use eqn. (11), and Fig. 3 shows the resulting graph of P as a function of x.

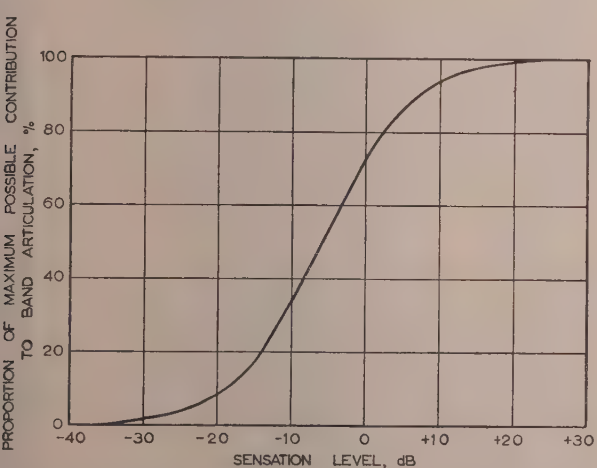

Fig. 3.—Proportion of maximum possible contribution to band articulation as a function of sensation level. (Function ψ.)

(3.3) Determination of the Parameters of w

The sound-articulation values given in Table 1 for low-pass lters can be converted to values of band articulation $\overline{P}$ by means of the function ϕ already determined (Fig. 2). Similarly, the corresponding values for high-pass filters can be converted to values of $1 - \overline{P}$ and so give the complementary values of band articulation. Both sets of results have been plotted in Fig. 4. It remains now to choose a simple form of curve to fit these points.

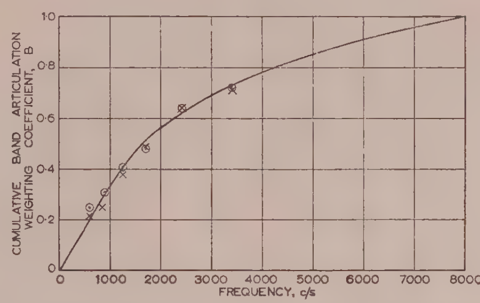

Fig. 4.—B, the cumulative value of function w, band articulation weighting coefficient, as a function of frequency.

× High-pass filter.
⊙ Low-pass filter.

There is considerable evidence (see, e.g., that assembled by Gabor[10]) that the ear treats tones up to about 1 000 c/s on a basis of equal weight per unit of frequency. Above this frequency the evidence points towards a logarithmic frequency basis, i.e. equal weight per unit of $\log f$. This would imply, when applied to the present problem, a linear relation between B and f up to a critical frequency f_c, and a linear relation between B and $\log f$ above this frequency. It is possible to choose f_c so that B' is continuous, and this has been done to give the curve shown in Fig. 4; it has also been assumed that $B' = 0$ outside the frequency range 30–8 000 c/s.

The parameters are as follows:

For $30 \leqslant f \leqslant 857$ $\quad B = 0·000365(f - 30)$;

for $857 \leqslant f \leqslant 8000$ $\quad B = 0·313 \log_\varepsilon f - 1·809$

or $B = 0·720 \log_{10} f - 1·809$.

Table 3

Limits of Mid-frequencies of 20 equally important Frequency Bands

Band number	Mid-frequency	Lower limit	Upper limit	Width	10 $\log_{10}$ (width)
	c/s	c/s	c/s	c/s	
1	98	30	167	137	21·4
2	236	167	304	137	21·4
3	372	304	441	137	21·4
4	510	441	578	137	21·4
5	646	578	715	137	21·4
6	784	715	852	137	21·4
7	926	852	1 000	148	21·7
8	1 083	1 000	1 174	174	22·4
9	1 272	1 174	1 378	204	23·1
10	1 493	1 378	1 617	239	23·8
11	1 752	1 617	1 897	280	24·5
12	2 055	1 897	2 226	329	25·2
13	2 411	2 226	2 612	386	25·9
14	2 830	2 612	3 064	452	26·6
15	3 319	3 064	3 595	531	27·3
16	3 894	3 595	4 219	624	28·0
17	4 570	4 219	4 951	732	28·7
18	5 363	4 951	5 809	858	29·3
19	6 293	5 809	6 817	1 008	30·0
20	7 385	6 817	8 000	1 183	30·7

The limits of 20 bands which correspond to equal increments of B have been calculated, and these, together with their mid-frequencies, are given in Table 3.

(4) APPLICATION OF THE DATA

The basic data assembled above are sufficient to enable the sound-articulation percentage to be calculated, given

(*a*) The spectrum and level of speech sounds at the ear.

(*b*) The spectrum and level of noise at the ear.

(*c*) That the noise is audible over the whole speech spectrum, i.e. that it is wholly above the threshold of audibility from 30 to 8 000 c/s.

The speech sounds which reach the ear depend upon the spectrum of acoustical speech power and the air-to-air attenuation of the speech link. The spectrum of speech pressure at the level at which articulation measurements are conducted is given in Table 2. The sensitivities of the sending and receiving ends of the high-quality telephone channel referred to here are given in Table 13 (Section 9), and the air-to-air sensitivity may be obtained by adding these together and allowing for the loss in the attenuator connecting them.

The noise which reaches the ear may result from circuit noise or room noise. If it comes from circuit noise, it is necessary to know the power-density spectrum at some point in the electrical circuit and the sensitivity of the circuit from this point to the ear. If room noise is present it will enter the ear by two paths, namely through sidetone and by leakage past the receiver earcap. Room noise reaching the ear by sidetone can be calculated from a knowledge of the power-density spectrum of the room noise and the air-to-air attenuation of the sidetone path. Similarly, the amount of noise entering the ear by leakage past the receiver earcap requires a knowledge of the acoustical attenuation of this path.

Several methods have been proposed for determining the attenuation of the earcap leakage path, but the most appropriate seems to be that based on pure-tone threshold measurements in the presence of ambient noise. The threshold of audibility is first determined in silence. A room noise of known level and spectrum derived from a white-noise generator is then set up at the position to be occupied by the receiver when applied to the ear but in the absence of the head and the receiver. The minimum audible level of pure tones is then redetermined and the shift in pure-tone threshold due to the presence of the noise is calculated. The shift in continuous-spectrum threshold will be the same, so that the continuous-spectrum threshold masked by the room noise which has leaked into the cavity between earcap and ear can be calculated. The level of noise which must have been present to cause this amount of masking can be calculated sufficiently accurately by taking the 'power difference', i.e. converting the levels from decibels to power ratios, subtracting the unmasked threshold power from the masked threshold power and reconverting to decibels. Table 13 shows the results obtained in this way for a high-quality moving-coil receiver with soft sponge-rubber ear-pad.

When the noise is inaudible over any part of the speech spectrum, account must be taken of the actual threshold of audibility; this can be done by assuming the threshold of audibility for continuous-spectrum sounds to be replaced by a continuous-spectrum noise of the same power-density spectrum. This hypothetical noise can then be combined by power addition with any actual noise present.

The pure-tone threshold of audibility of the Post Office articulation crew has been measured using the receiving end of a high-quality telephone channel. The level of tone which was just audible was determined for a number of frequencies from 300 to 6 000 c/s. The corresponding pressures measured in a real ear were determined from the known sensitivities of the receiving end. The results agree reasonably well with those of Dadson and King[21, 27] up to about 2 500 c/s but are somewhat higher above this frequency. This effect may perhaps be accounted for by the higher average age of the crew. (The Dadson and King results are based on subjects aged 18–25 years.)

For calculations of articulation the threshold for continuous-spectrum sounds is required, expressed relative to 1 c/s bandwidth, i.e. in dynes per square centimetre per cycle per second or, as here, in decibels relative to the datum of 0·000 2 dyne/cm² per cycle per second. This is obtained from the pure-tone results by taking into account Fletcher's 'critical bandwidths'. A critical bandwidth is the width in cycles per second of a band of continuous-spectrum sound at the threshold of audibility (let this level relative to datum power per cycle per second be denoted by y_1), such that y_1 integrated over this bandwidth is equal to the threshold level of a pure tone at the centre of the band in frequency. Let this pure-tone threshold level be y_2. The pure-tone threshold curve, plotted in decibels relative to datum power, is therefore located above the continuous-spectrum threshold curve, plotted in decibels relative to datum power per cycle per second, by an amount equal to

$$y_2 - y_1 = K = 10 \log_{10} \text{(critical bandwidth)}$$

K is tabulated by French and Steinberg (Table VII), and by Fletcher and Galt (Table XXX). The continuous-spectrum thresholds corresponding to the Post Office results for the frequency range 300–6 000 c/s are given in Table 2, in which the results for frequencies below 300 c/s have been derived from those of Dadson and King. Above 6 000 c/s the Post Office results have been extrapolated at a slope derived from other published data for older subjects.

(5) EXAMPLES

(5.1) High-quality Microphones and Receivers

The first examples given below are of telephone channels based on a high-quality telephone channel and have been chosen to give a reasonably severe test of the agreement between measured results and the corresponding calculated values.

Calculation of the articulation score for a given telephone circuit consists in evaluating the expression in eqn. (1) given the functions ϕ (Fig. 2), ψ (Fig. 3) and B (Fig. 4), together with the speech/noise ratio at the ear as a function of frequency. The last item is calculated from the speech spectrum (Table 2), the air-to-air sensitivity of the circuit as a function of frequency and the threshold of audibility masked by any noise present. It is convenient to perform the calculations in twenty 'equally important' frequency bands, because, once the mid-frequencies of these have been chosen, B is disposed of. A convenient computational procedure is given in Section 9, which also contains the necessary data in a convenient form.

The first two examples (Table 4) each give the measured and calculated sound-articulation percentages for five settings of the attenuator connected between the sending and receiving ends of a high-quality telephone channel.

The measured articulation percentages are reliable to within about $\pm 1\%$.

The room noise, which had a spectrum typical of noise likely to be encountered in telephone subscribers' premises[8] (see Table 2), was measured with a sound-level meter[9] calibrated to a datum sound pressure at 1 000 c/s of 0·000 2 dyne/cm².

It is frequently convenient to express the performance of a telephone channel in terms of the setting of the attenuator connecting the sending and receiving ends which yields a sound

Table 4

Listening condition	Attenuator setting	Sound articulation	
		Measured	Calculated
	dB	%	%
In silence	60	97·5	98
	65	94	95
	70	87	88
	75	75	74
	80	50	50
In 60 dB room noise, with sidetone facility	25	98	99
	30	96	98
	35	87	91
	40	62	75
	45	31	47

rticulation of 80%; such a setting is given the symbol $x_{0\cdot 8}$. The results for a number of telephone channels, including the two eferred to above, are given in Table 5 in this form. These hannels are all based on the same high-quality telephone channel nd differ only in respect of the listening conditions and of the resence or absence of a band-pass filter or other transmission lement inserted between the attenuator and the receiving end.

values, to validate the calculation technique for the range of conditions likely to be encountered in making articulation measurements on practical commercial telephone channels.

(5.2) Commercial Telephone Sets

The articulation calculation technique can clearly be applied in the same manner to practical telephone channels, provided that the appropriate sensitivities are known. Unfortunately, it is by no means easy to decide which are the appropriate means of measurement for commercial transmitters and receivers. No completely satisfactory solution has so far been obtained, but the procedure indicated below, which has been arrived at largely by a cut-and-try process, is a reasonably good compromise.

(5.2.1) Transmitters.

The carbon-microphone type of telephone transmitter, at present universally used in public telephone systems on account of its high sensitivity, introduces several serious difficulties of measurement.

Being a handset microphone, spoken into at a close but relatively undefined distance, it is subject to a rather uncertain level of speech pressure. Amplitude distortion is also a serious matter, so that the sensitivity itself is dependent upon the sound pressure. These difficulties are circumvented in articulation measurements by a trained crew by adopting a fixed distance

Table 5

Channel number	Listening condition	Transmission element	Value of $x_{0\cdot 8}$	
			Measured	Calculated
			dB	dB
1	In silence	None	73·6	73·5
2	In silence	300–3 400 c/s band-pass filter (b.p.f.) and network A	50·7	48·5
3	In silence	B.P.F. and network B	32·7	32·5
4	In 60 dB room noise	B.P.F.	59·9	62·5
5	In 60 dB room noise	B.P.F. and network A	37·4	40·0
6	In 60 dB room noise	B.P.F. and network B	19·7	22·5
7	In 60 dB room noise with side-tone facility	None	37·3	39·0
8	In 60 dB room noise with side-tone facility	B.P.F.	33·6	36·0

The measured values of $x_{0\cdot 8}$ may be relied upon to within ±2 dB (95% confidence interval), except for channels 1 and 7 which have been used more frequently and may be relied upon o within ±1 dB.

The band-pass filter was designed to simulate the charac- eristic of a channel of a carrier system having a channel spacing f 4 kc/s.

Network A is an equalizing network designed to simulate the pproximate frequency-response characteristic of a Post Office Transmitter, Inset, No. 13'. Network B is an equalizing network esigned to simulate the overall air-to-air sensitivity charac- eristic of a typical telephone connection.

The sidetone facility used with the high-quality channel is rranged so that a noise voltage (Hoth spectrum) picked up by n auxiliary microphone circuit appears across the receiver erminals. This voltage produces a sound pressure at the ear qual to that which would exist under free field conditions, in he absence of the receiver, due to the room noise present. The arrangement reduces the effect of variations of leakage path etween the receiver ear-pad and the ear, which, if present, would limit the precision of experiments.

The agreement shown in the above examples between the neasured and the calculated values is considered sufficiently lose, bearing in mind the limited precision of the measured

between lips and mouthpiece opening and by controlling the vocal level.

Articulation measurements are conducted at reference vocal level, i.e. with the speech pressure controlled to a level of 1 dyne/cm^2 at a distance of 13¼ in (33·7 cm) in front of the lips. The distance between lips and mouthpiece opening for the present British Post Office Telephone No. 164 Handset when the standardized talking position is adopted is 2·5 cm. Taking the conclusion of Dunn and Farnsworth[6] that the equivalent point source is situated 0·6 cm behind the lips, the distance between this point and the centre of the mouthpiece opening is therefore 3·1 cm, and between the equivalent point source and the point at which the speech pressure is 1 dyne/cm^2 is 34·3 cm. By invoking the inverse-square law for sound power, the free-field sound pressure at the point occupied by the mouthpiece opening is 11 dynes/cm^2. This pressure is, like that in terms of which reference vocal level is specified, defined in terms of the reading of a speech voltmeter associated with a calibrated micro-phone; the instantaneous sound pressure, of course, ranges much higher, perhaps to more than 100 dynes/cm^2.

Because the carbon microphone is non-linear and gives rise to amplitude distortion, it does not follow that a sensitivity/frequency characteristic measured with pure tones should use the same pressure as the speech pressure at which it will be used.

Various methods have been suggested and tried,[7, 18] but the best results, when the pure-tone sound pressure has been restricted to one value independent of frequency, have been obtained at a pressure of 50 dynes/cm^2.

The agreement between measured and calculated articulation results is conveniently illustrated by quoting the amount of loss which must be introduced to reduce the sound articulation to 80%, (*a*) for a high-quality but limited bandwidth (300–3 400 c/s) telephone channel with a relatively distant-speaking linear microphone (so that the sensitivity is in little doubt), and (*b*) for the same channel but with the sending end replaced by a local telephone circuit containing a carbon-microphone handset. The difference between these two amounts of loss (termed the sending rating) will be largely independent of the articulation crew, on the one hand, and the precise accuracy of the parameters of the articulation calculation data on the other. Table 6

Table 6

Subscriber's set	Measured rating	Calculated rating
	dB	dB
A	−13·6	−15
B	−14·6	−14·5

shows the measured and calculated sending ratings of two types of Post Office subscribers' sets, both using the Transmitter, Inset, No. 13; set A uses Coil, Induction, No. 18.35A and set B, Coil, Induction, No. 27. Each set is associated with a subscriber's line of 450 ohms in 10 lb cable (2·56 miles) connected to a 50-volt non-ballast feeding bridge having 200 + 200-ohm relays. Listening is in the presence of 60 dB room noise, and the sidetone facility is associated with the high-quality receiving end. The measured ratings have 95% confidence intervals of ±1 dB, and the calculated ratings are expressed to the nearest 0·5 dB.

The sensitivity discussed in the foregoing is that which applies to the speech input; it is necessary also to consider the sensitivity of the transmitter to room-noise excitation. A room-noise level of 60 dB corresponds to a weighted sound pressure of 0·2 dyne/cm^2. Under pure-tone conditions the sensitivity would be extremely low at such a sound pressure. In practice it is found that the sensitivity applicable corresponds to that measured at a sound pressure of 3 dynes/cm^2. There is also evidence that the same sensitivity is maintained even at lower levels of room noise; the high sensitivities may well be due to the slight agitation of the handset while held in the hand for listening.

For the present, therefore, it seems best to measure the sensitivity of a carbon-microphone telephone handset at a free-field sound pressure of 50 dynes/cm^2 for speech and at 3 dynes/cm^2 for room-noise excitation. This conclusion is based on experience with the Transmitter, Inset, No. 13 used in the Telephone No. 164 Handset and certainly requires caution before being applied to any handset which is substantially different in characteristics.

(5.2.2) Receivers.

The sensitivities of telephone receivers are commonly measured by means of an artificial ear having a cavity of volume 3 cm^3 (see B.S. 2042: 1953).[26] Such sensitivities, when used in articulation calculations, yield results which are considerably higher (about 6 dB) than those obtained by measurement. Subjectively measured sensitivities are also lower than those from artificial-ear measurements by about 6 dB, independently of frequency. This discrepancy is believed to be due to the fact that artificial ears are designed to simulate a particularly careful application of the receiver earpiece to the ea which does not apply under articulation measurement condition for commercial handset telephones having hard ear-caps. Th difficulty does not arise with the receivers of the high-qualit telephone channel, because they have soft ear-pads and a muc larger volume of air is enclosed. The artificial ear used for thes receivers takes due account of this larger volume.

Use of a sensitivity/frequency characteristic 6 dB lower tha that obtained with the 3 cm^3 artificial ear has been found to yiel reasonable agreement between measured and calculated articula tion scores. This rule applies equally well to the Post Offic Receiver, Inset, No. 1L, which has a very peaked sensitivit characteristic, and to the Receiver, Inset, No. 2P, which is ver smooth in characteristic.

Examples are given below after discussion of the other factor affecting reception.

(5.2.3) Ear-cap Leakage and Sidetone Attenuation.

With a telephone handset in the presence of room nois reception is impaired by leakage of this noise past the receive ear-cap into the listening ear and by transmission of the roon noise through the sidetone path (transmitter, electrical circu and receiver). Noise entering the non-listening ear may b neglected.

The subjective method described in Section 4 yields, fo receivers with hard ear-caps, attenuations which are somewha too high for good agreement between articulation measurement and calculations; accordingly the lower values recorded i Table 13 (Section 9) have been found to be more appropriate This disagreement is probably due to the excessive care used i placing the receiver to the ear during threshold measurements.

A similar subjective method may be employed to determin the attenuation of the sidetone path, and the results obtaine are in good agreement with the attenuation calculated from th 3-dynes/cm^2 transmitter sensitivity characteristic, electrica measurements on the induction coil and the artificial-ea sensitivity of the receiver reduced by 6 dB, as discussed i Section 5.2.2.

(5.2.4) Receiving Performance.

The choice described very briefly above of methods fo measuring the sensitivity of the transmitter to room-nois excitation, the receiver sensitivity and the ear-cap leakage-pat attenuation has been based on a rather complicated stud directed to securing good agreement between measured an calculated articulation scores over a wide range of listening con ditions. The agreement is illustrated in Table 7 for one conditio

Table 7

Subscriber's set	Measured rating	Calculated rating
	dB	dB
A	+13·5	+13
B	+21·1	+21·5

which involves all the factors discussed. Receiving ratings ar given, obtained in a manner analogous to the sending ratin described in Section 5.2.1. Both sets use Transmitter, Inset No. 13; set A uses Coil, Induction, No. 18.35A (rather poo sidetone suppression) and Receiver, Inset, No. 1L (peake sensitivity characteristic), and set B uses Coil, Induction, No. 2 (good sidetone suppression on the subscriber's line associated and Receiver, Inset, No. 2P (smooth characteristic). Each se is associated with a subscriber's line of 450 ohms in 10 lb cabl

·56 miles) connected to a 50-volt non-ballast feeding bridge ving 200 + 200-ohm relays. Listening is in the presence of dB room noise.

The measured ratings have 95% confidence intervals of ±1 dB, d the calculated ratings are expressed to the nearest 0·5 dB.

2.5) Overall Performance of a Commercial Telephone Channel.

The overall effect of the various choices of measuring methods plicable for commercial telephone sets is illustrated in Table 8 a comparison of the sound articulation scores obtained by

Table 8

Subscriber's set (each end)	Junction attenuator setting	Sound articulation	
		Measured	Calculated
	dB	%	%
A	20	91·3	94
	25	87·8	92
	30	83·3	87
	35	76·5	79
	40	68·1	65
B	30	91·5	94
	35	90·4	91
	40	80·1	86
	45	68·5	76
	50	54·7	59

easurement and calculation for two complete commercial lephone channels. The results are given for a number of settings the attenuator connecting two similar commercial local lephone circuits. A band-pass filter (300–3 400 c/s) was cluded in the junction, and listening was in the presence of dB room noise of typical spectrum. In both examples the ubscriber's line consisted of 450 ohms of 10 lb cable and the eding bridge was of the 50-volt non-ballast type. The measured ores have been taken from two selected experiments which elded the most typical results. The confidence intervals of the easured scores are about ±4% at 80% but become smaller wards 100% and larger at the lower percentages involved.

Sets A and B were of the same types as described in Sections 2.1 and 5.2.4.

The attenuator settings which correspond to 80% sound ticulation ($x_{0\cdot8}$) have also been determined for these circuits nd the results are given in Table 9. The measured values have

Table 9

Subscriber's set (each end)	Value of $x_{0\cdot8}$	
	Measured	Calculated
	dB	dB
A	31·9	34·5
B	40·2	43·5

5% confidence intervals of about ±1 dB and the calculated alues are expressed to the nearest 0·5 dB.

It is interesting to note that the relative results (set B minus et A) are in better agreement than the actual $x_{0\cdot8}$ values, namely easured 8·3 and calculated 9·0 dB. Experience has shown at comparisons of telephone channels which differ only slightly ay be relied upon to a much greater extent than measures of bsolute performance or comparisons between widely differing annels.

(6) FURTHER STUDY

Clearly, a great deal of further study of the subject is required, especially of the appropriate measurement of transducer sensitivities. It cannot be claimed that calculated results can always be relied upon without some supporting measurements, but the present stage of the calculation technique permits a very broad field to be explored with the aid of only a few actual measurements.

It is not possible at present to say whether the discrepancies that do exist are due to shortcomings of the theory or to ignorance of the precise physical conditions which obtain during the articulation measurements. It is, however, considered that the theory is sufficiently soundly based to justify further study of the physical conditions.

It must be admitted that articulation as a measure of telephone transmission performance has its limitations, particularly in the degree to which the conditions of measurement approximate to the actual conditions under which the public telephone network is used. In practice, various allowances must be made for the influences which the circuit itself has on the behaviour of the user. For example, articulation measurements are made at constant vocal level and with a fixed speaking position, whereas it is known that loud sidetone or high loss in the circuit affects markedly the speech output produced by the user.[24] Such artificialities can largely be removed by making telephone assessments under more appropriate and therefore less formal conditions and using untrained subjects. The general problem of assessment has been discussed elsewhere,[25] but it is worth noting here that the theoretical framework described above may well be applicable also for assessment methods other than articulation. It is already clear that the relative importance of certain factors is different under normal conditions of use from that found during articulation measurements with a trained crew.

(7) ACKNOWLEDGMENTS

Acknowledgment is made to the Engineer-in-Chief of the Post Office for permission to make use of information contained in the paper. The work on which this study has been based is by no means that of the authors alone, and tribute must be paid to their many colleagues whose co-operation has made such a large study possible, from those concerned with electro-acoustical measurements to those who have performed most of the laborious computing. Special tribute is owed to Mr. J. O. Ackroyd, who stimulated the initial interest in the subject.

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(9) APPENDIX

A convenient method of performing the calculations is illustrated here by the following problem.

It is desired to estimate the effect upon transmission of the presence of a line noise consisting of band-pass-filtered white noise of level −60 dBm measured with the CCIF psophometer. The effect is to be expressed as an 'impairment', i.e. as the amount of loss which must be removed from the circuit when the noise is present in order to restore a given level of performance which was obtained with the noise absent. The level of performance under consideration will be defined as 80% sound articulation. The problem is therefore (*a*) to calculate the amount of loss x_1 which must be inserted to reduce the sound articulation to 80% in the absence of the noise, (*b*) to calculate the amount of loss x_2 required to reduce the sound articulation to 80% in the presence of the noise, and (*c*) to calculate the impairment, which is $x_1 - x_2$.

The telephone circuit considered consists of two modern-type subscribers' sets each with typical subscribers' lines of 1 mile of 6½ lb cable (270 ohms). Listening is in the presence of 50 dB room noise. Table 13 gives the sensitivity and attenuation data which will be used. Table 2 gives a summary of various basic data which will also be required.

The computations are conveniently set out in a series of Tables for which blanks having the necessary headings can be prepared if a large number of articulation calculations are to be made. For convenience in describing the computing steps, the Tables, which are assembled at the end of this Section, will be referred to as follows:

Chart A (Table 13) Sensitivity and attenuation data.
Chart B (Table 14) Calculation of masked hearing threshold.
Chart C (Table 15) Calculation of speech-masked threshold ratio.
Chart D (Table 16) Calculation of sound articulation.

The computations will be described column by column, and it is implied that all the figures of a column are treated similarly using corresponding figures in the other columns referred to. For brevity, column 3 of chart B will be referred to as B3; similarly C4 will denote column 4 of chart C, and so on.

Chart A (*Table* 13).

The sending and receiving sensitivities, expressed in units of volts and dynes per square centimetre, together with ear-cap leakage and sidetone-path attenuations for the local telephone circuit concerned, are assembled on chart A. Columns 7–10 only are used in this example.

Chart B (*Table* 14).

Chart B yields the threshold of audibility masked by the noise present. The effect of room noise is treated first and line noise allowed for afterwards. The steps are as follows.

Enter room noise (see Table 2) in B3.
Enter sidetone-path attenuation in B4 from A10.
B5 = B3 − B4.
Enter ear-cap leakage attenuation in B6 from A9.
B7 = B3 − B6.

B8 is obtained by 'power summation' of B5 and B7. This is achieved with the aid of Table 10 which relates the amount in decibels which must be added to the higher of the two levels as a function of the difference between the two levels. Care must be exercised in taking correct account of algebraic signs.

Enter threshold of audibility (Table 2) in B9.

B10, which is the masked threshold when room noise only is present, is obtained by 'power summation' of B8 and B9.

Columns (11) to (14) permit the effect of line noise also to be allowed for.

Enter line noise in B11. The line noise should be expressed relative to a datum of 0·0002 volts (−74 dB relative to 1 volt) in a 1 c/s bandwidth; this saves later conversion of sound pressures in dynes per square centimetre to the basis of 0·0002 dyne/cm² in a 1 c/s bandwidth, which is used for the other threshold data.

Table 10

WER SUMMATION' OF TWO QUANTITIES EXPRESSED IN DECIBELS

Difference between the two levels	Amount to be added to higher level
dB	dB
0	3
1	3
2	2
3	2
4	1
5	1
6	1
7	1
8	1
9 or greater	0

Enter receive-end sensitivity in B12 from A8.
B13 = B11 + B12.
B14, which is the masked threshold when line noise as well as om noise is present, is obtained by 'power summation' of 0 and B13.

art C (*Table* 15).
Chart C enables the speech level at the ear to be calculated, d hence, using the results of chart B, the speech-masked reshold ratio.
Enter sending sensitivity in C3 from A7.
Enter loss of the band-pass filter in C4.
Enter receiving sensitivity in C5 from A8.
C6 = C3 − C4 + C5.
Enter speech at appropriate level (11 dynes/cm^2 in this case, om Table 2) in C7.
C8 = C6 + C7.
C9, which is the speech/masked-threshold ratio when room ise only is present, is given by C8 − B10 (for 0 dB setting of attenuator).
C10 is the corresponding speech/masked-threshold ratio when e noise is also present and is given by C8 − B14.

art D (*Table* 16).
C9 and C10 must be adjusted to allow for the setting of the tenuator connected, in addition to the band-pass filter, in the nction connecting sending and receiving ends. It is desired re to determine x_1 and x_2, namely the settings to correspond 80% sound articulation, respectively without and with the e noise present. A number of settings must be chosen, the ticulation percentage calculated for each and the values of and x_2 obtained by interpolation.
The calculations are shown on chart D for two settings of the tenuator under each noise condition. It is often necessary to lculate for three or four settings before satisfactory interpola-on is possible (to the nearest 0·5 dB).
The procedure is as follows for the no-line-noise condition. D3 enter C9 minus the attenuator setting (in this case 50 dB).
In D4 enter 100P from Table 11.
The entry in D4 for band 15 is shown in brackets because the t-off frequency of the band-pass filter falls in the band so that ly 80% of band 15 is effective. The second figure in D4 for nd 15 is therefore 80% of the value in brackets.
D4 is summed to give Σ 100P.
The means value is given by $100\overline{P} = \frac{1}{20}\Sigma\, 100P$

Table 11

100P AS A FUNCTION OF SPEECH/MASKED-THRESHOLD RATIO

(i) Positive values of speech-threshold

	0	1	2	3	4	5	6	7	8	9
0	73	77	80	82	85	87	89	90	92	93
10	94	95	96	96	97	97	98	98	98	99
20	99	99	99	99	99	100	100	100	100	100

(ii) Negative values of speech-threshold

	0	−1	−2	−3	−4	−5	−6	−7	−8	−9
0	73	70	66	62	58	54	50	46	42	38
−10	34	30	27	23	20	18	15	13	11	10
−20	8	7	6	5	4	4	3	3	2	2
−30	2	1	1	1	1	1	1	0	0	0

Table 12

PERCENTAGE SOUND ARTICULATION AS A FUNCTION OF PERCENTAGE BAND ARTICULATION

Band articulation $100\overline{P}$, %										
Units / Tens	0	1	2	3	4	5	6	7	8	9
0	0	1	3	4	6	9	12	15	20	23
10	26	29	32	35	38	41	44	47	49	52
20	54	57	59	61	63	65	67	69	71	72
30	74	75	76	78	79	80	81	82	83	84
40	85	85	86	87	87	88	89	90	90	91
50	91	92	92	93	93	94	94	94	95	95
60	96	96	96	96	97	97	97	97	98	98
70	98	98	98	98	98	99	99	99	99	99
80	99	99	99	99	99	99	99	100	100	100
90	100	100	100	100	100	100	100	100	100	100

The percentage sound articulation (100*s*) is given in Table 12 for $100\overline{P}$.

The same procedure is then followed in D5 and D6 for another choice of attenuator setting (55 dB). The 55 dB setting yields a sound articulation percentage very close to 80%; similar calculations (not shown) for 56 dB setting yield 78%, whence by interpolation x_1 = 55·5 dB to the nearest 0·5 dB.

D7 to D10 illustrate the procedure when line noise is also present.

In D7 enter C10 minus the attenuator setting (45 dB).

In D8 enter 100P from Table 11.

D8 is then treated as described for D4.

Columns D9 and D10 show similar computations for a setting of 50 dB. Further calculations (not shown) for settings of 47 and 48 dB yield sound articulations of 82% and 79%, whence by interpolations x_2 = 47·5 dB.

The impairment due to this level (−60 dBm) of line noise at the input of the receiving local telephone circuit is therefore calculated as $x_1 - x_2$ = 55·5 − 47·5 = 8 dB. Measurement gave 9·3 dB with a 95% confidence interval of ±2 dB.

Table 13

CALCULATION CHART A

Sensitivity and attenuation data

Band number	Mid-frequency	High-quality telephone channel				Typical commercial local telephone circuit			
		Send sensitivity rel. 1 volt per dyne/cm^2	Receive sensitivity rel. 1 dyne/cm^2 per volt	Ear-cap leakage path attenuation	Sidetone path attenuation	Send sensitivity rel. 1 volt per dyne/cm^2	Receive sensitivity rel. 1 dyne/cm^2 per volt	Ear-cap leakage path attenuation	Sidetone path attenuation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	c/s	dB	dB	dB	dB	dB	dB	dB	dB
1	98	−1	20	6	2	−43	14	0	38
2	236	1	21	13	−2	−41	27	4	29
3	372	0	20	17	0	−40	32	8	24
4	510	0	20	20	0	−39	33	10	23
5	646	0	20	23	0	−38	34	13	22
6	784	0	21	27	−1	−35	34	15	22
7	926	0	22	31	−2	−32	34	18	20
8	1 083	0	22	30	−2	−29	34	21	16
9	1 272	0	22	28	−2	−25	34	23	6
10	1 493	0	24	26	−2	−26	36	24	−3
11	1 752	0	24	26	−4	−25	36	24	3
12	2 055	0	26	27	−4	−25	31	23	15
13	2 411	−1	26	30	−4	−28	28	21	19
14	2 830	0	27	28	−6	−32	32	19	12
15	3 319	0	28	22	−8	−38	27	18	23
16	3 894	1	28	Data	−8			Data	Attenuation
17	4 570	1	26	unreliable	−6	Sensitivities		unreliable	rises
18	5 363	1	25	above	−6	fall steeply		above	steeply
19	6 293	2	28	band 15	−10	above band 15		band 15	above
20	7 385	0	31		−10				band 15

NOTE 1.—Send sensitivity measured with free-field sound pressure at centre of mouthpiece opening of 50 dynes/cm^2 and p.d. measured across 600-ohms termination.
NOTE 2.—Sound pressure from receiver measured with 3 cm^3 artificial ear, but results decreased 6 dB uniformly with frequency. 600-ohms source used and sensitivity expressed in terms of p.d. measured with the local telephone circuit replaced by a 600-ohms termination.
NOTE 3.—Sidetone path attenuation calculated from transmitter measurements at 3 dynes/cm^2 free-field sound pressure at centre of mouthpiece opening and receiver sound pressure measurements as Note 2.

Table 14

CALCULATION CHART B

Calculation of threshold of audibility masked by noise

Band number	Mid-frequency	Effect of room noise only								Additional effect of line noise			
		Room noise, 50 dB level	Sidetone path attenuation	Sidetone noise at ear	Ear-cap leakage attenuation	Noise at ear by leak	Total noise at ear	Hearing threshold	Threshold masked by room noise	Line noise, −60 dBm level	Receive-end sensitivity	Line noise at ear	Threshold masked by line noise and room noise
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	c/s	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
1	98	33	38	−5	0	33	33	19	33	−33	14	−19	33
2	236	27	29	−2	4	23	23	3	23	−26	27	1	23
3	372	24	24	0	8	16	16	−2	16	−23	32	9	17
4	510	22	23	−1	10	12	12	−6	12	−22	33	11	15
5	646	20	22	−2	13	7	7	−10	7	−21	34	13	14
6	784	18	22	−4	15	3	4	−12	4	−21	34	13	13
7	926	18	20	−2	18	0	2	−14	2	−21	34	13	13
8	1 083	16	16	0	21	−5	1	−14	1	−21	34	13	13
9	1 272	15	6	9	23	−8	9	−13	9	−21	34	13	14
10	1 493	14	−3	17	24	−10	17	−12	17	−21	36	15	19
11	1 752	13	3	10	24	−11	10	−11	10	−21	36	15	16
12	2 055	12	15	−3	23	−11	−2	−11	−2	−21	31	10	10
13	2 411	10	19	−9	21	−11	−7	−13	−6	−21	28	7	7
14	2 830	9	12	−3	19	−10	−2	−10	−1	−21	32	11	11
15	3 319	8	23	−15	18	−10	−9	−8	−5	−21*	27	6*	6*
16	3 894	6						−7					
17	4 570	4						−9					
18	5 363	2						−9					
19	6 293	−1						−5					
20	7 385	−4						−3					

* Cut-off frequency of band-pass filter includes 80% of band 15.

Table 15

CALCULATION CHART C

Calculation of ratio of speech level to masked threshold

Band number	Mid-frequency	Send-end sensitivity	Junction loss	Receive-end sensitivity	Attenuation setting 0 dB			Speech to masked threshold ratio	
					Overall sensitivity	Speech, 11 dynes/cm²	Speech at ear	Room noise only present	Line noise and room noise present
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	c/s	dB	dB	dB	dB	dB	dB	dB	dB
1	98	−43	12	14	−41	61	20	−13	−13
2	236	−41	5	27	−19	67	48	25	25
3	372	−40	2	32	−10	68	58	42	41
4	510	−39	1	33	−7	67	60	48	45
5	646	−38	0	34	−4	63	59	52	45
6	784	−35	0	34	−1	60	59	55	46
7	926	−32	0	34	2	57	59	57	46
8	1083	−29	0	34	5	55	60	59	47
9	1272	−25	0	34	9	53	62	53	48
10	1493	−26	0	36	10	51	61	44	42
11	1752	−25	0	36	11	49	60	50	44
12	2055	−25	0	31	6	48	54	56	44
13	2411	−28	0	28	0	47	47	53	40
14	2830	−32	0	32	0	45	45	46	34
15	3319	−38	0*	27	−11*	43	32*	37*	26*
16	3894					40			
17	4570					37			
18	5363					36			
19	6293					35			
20	7385					34			

* Cut-off frequency of band-pass filter includes 80% of band 15.

Table 16

CALCULATION CHART D

Calculation of sound articulation

Band number	Mid-frequency	Room noise only present				Line noise and room noise present			
		Setting 50 dB		Setting 55 dB		Setting 45 dB		Setting 50 dB	
		Speech to threshold ratio	100P	Speech to threshold ratio	100P	Speech to threshold ratio	100P	Speech to threshold ratio	100P
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	c/s	dB		dB		dB		dB	
1	98	−63	0	−68	0	−58	0	−63	0
2	236	−25	4	−30	2	−20	8	−25	4
3	312	−8	42	−13	23	−4	58	−9	38
4	510	−2	66	−7	46	0	73	−5	54
5	646	2	80	−3	62	0	73	−5	54
6	784	5	87	0	73	1	77	−4	58
7	926	7	90	2	80	1	77	−4	58
8	1083	9	93	4	85	2	80	−3	62
9	1272	3	82	−2	66	3	82	−2	66
10	1493	−6	50	−11	30	−3	62	−8	42
11	1752	0	73	−5	54	−1	70	−6	50
12	2055	6	89	1	77	−1	70	−6	50
13	2411	3	82	−2	66	−5	54	−10	34
14	2830	−4	58	−9	38	−11	30	−16	15
15	3319	−13*	(23) 18	−18*	(11) 9	−19*	(10) 8	−24*	(4) 3
16	3894								
17	4570								
18	5363								
19	6293								
20	7385								
		Σ 100P	914		711		822		588
		100P, %	45·7		35·6		41·1		29·4
		100s, %	89		81		85		73

* Cut-off frequency of band-pass filter includes 80% of band 15. Values of 100P given in brackets would apply if whole of band 15 were effective; values to be used here are 80% of the values in brackets.

DISCUSSION ON 'A TRANSATLANTIC TELEPHONE CABLE'*

Before the NORTH MIDLAND CENTRE *at* LEEDS 11*th November, and the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE 14*th November*, 19

Mr. C. A. Beer (*at Leeds*): The existing radio systems across the Atlantic are, of course, very satisfactory at some times and quite impossible at others, and the cable appears to be the only solution which can now be envisaged almost regardless of cost. Nevertheless, it would be interesting to know the percentage time that radio is now serviceable. It is noticeable that microwave radio is to be used at the American end, and presumably can be regarded as quite adequate on the grounds of stability.

There are, no doubt, many factors which will lead to the success of this venture, such as the reliability of the cables and valves, while the feedback amplifiers, with their stability and other marked advantages, will play a major part in balancing the loss of 2000 dB or more in the submarine cables concerned. There is, too, the wide difference of attenuation over the frequency range to be allowed for.

The maintenance of the system would appear possibly to be the biggest problem. For example, if all components have an average life of 20 years, even allowing for duplicate amplifiers, I can imagine that, in the period 16–24 years hence, troubles will reach a steady pitch and a cable ship could conceivably be engaged in a continuous shuttle service across the Atlantic. We could, of course, derive some comfort from radio channels for bridging gaps in the submarine service. On a matter of detail affecting maintenance, I have always felt that the long tapered design of the American repeater must have fundamental advantages in terms of handling and movement over the more abrupt repeater-cable junction in the British design.

Is the noise contained in the system to all intents and purposes zero, apart from valve noise, assuming that the cable is lying on the sea bed?

The technique now to be used can no doubt be applied to land practice, especially on the longer distances in America and Canada. However, some of the marked advantages to be exploited in the submarine system should be given serious consideration in Britain.

Mr. N. F. Sephton (*at Leeds*): I have watched cable being stored into, and paid out of, cable-ship tanks, and it seems to me that the tendency to kink is due inherently to the fixed cable tank. With the small ships and heavy cables of earlier days, fixed tanks were necessary, but I wonder whether in the future design of larger ships some kind of rotating tank might not be devised for the modern coaxial cables, which are of smaller diameter than the old continuously loaded a.s.p.c. telephone cables, especially as the cable is laid, not as a whole, but in ocean blocks.

Although it can safely be assumed that the fault liability of a cable at the bottom of the Atlantic, free from the menaces of dragged anchors and with a very high ratio of deep-sea length to shore-end length, will be very much lower than that of cable laid on the Continental Shelf, it seems certain that during 20 years some faults will occur. What type of localization test will be used and what sort of accuracy of localization is expected? There is no question of locating to a repeater section and making a sub-localization. An accuracy of 1% might be good testing, but it represents quite a length on a 2000-mile cable. And even when the distance along the cable has been accurately measured, the finding of a faulty piece of cable laterally, not to mention vertically, in the Atlantic will be a considerable effort of navigation, although there was reassurance in the account of how the end of an ocean block, lost after the marker buoy had bl away, was located and picked up seemingly without m difficulty.

Colonel J. R. Sutcliffe (*at Newcastle upon Tyne*): Owing to presence of the repeaters, normal d.c. methods of fault locat will become less applicable. Are there any advantages in hav both-way repeaters? Will the authors explain the statemen Section 4 regarding twin cables with traffic rapidly grow beyond the capacity of a single-cable system?

Mr. F. W. Allan also contributed to the discussion at Newca upon Tyne.

Mr. Mervin J. Kelly, Sir Gordon Radley, Messrs. G. Gilman and **R. J. Halsey** (*in reply*): It is not surprising that discussion should centre largely on the possible breakdown the system. Mr. Beer suggests that the *average* life of com nents may be 20 years, but this would be quite inadequate. I of course, impossible to be precise in the prediction of repe life, even on a statistical basis, but the order of fault liabi which we have in mind is, perhaps, one fault per ten repeater the first 20 years. If the standard deviation is 25% of average life of a repeater, the latter must then be about 30 ye and that of components very much greater. He and Mr. Al can be assured that the quality built into the components p them in a very special class, but at a price which would proh their general use in land-based equipment. Nevertheless, will be very surprising if some of the techniques develo for submerged repeaters are not ultimately reflected in la systems.

In the event of a fault it is highly probable that it will possible to keep the repeaters energized; the supervisory equ ment provided in the repeaters will then indicate in wh repeater, or repeater section, the fault lies. In this connect both-way repeaters have the advantage that measurements be made from the two ends of the system. Conductor resista measurements can help, but the current-dependent resistance the repeaters, as well as earth currents, render such measureme unprecise. Capacitance measurements made during the lay operation can be of assistance in the unlikely event of an insula discontinuity. The repair of a fault in deep water will invo the addition of 5–10 nautical miles of cable and a special rep repeater, as well as the replacement of any repeater which m be faulty.

Space does not permit of discussion on the relative merits one-way and two-way cables, but it will be clear to Col. Sutcl that, if circuit requirements are such that excessive termi voltages are required to energize the repeaters necessary in c cable, two cables must be provided. These may be equip for either one-way or both-way transmission.

Valve noise does not make a serious contribution to circ noise, which consists mainly of resistance noise and intermodu tion noise. Microwave radio links are commonly used internal circuits in the United States and Canada, and inclusion of such a link in the transatlantic system should n degrade its performance significantly. By contrast, the existi transatlantic radio circuits are serviceable for, perhaps, 65–9 of the time under normal conditions and are practically usel at times of severe ionospheric disturbance.

Mr. Sephton's suggestion that cable tanks should rotate already been considered, but is not thought to be particula advantageous except, possibly, for power cables; the mechani difficulties are considerable.

* KELLY, MERVIN J., RADLEY, SIR GORDON, GILMAN, G. W., and HALSEY, R. J.: Paper No. 1741, September, 1954 (see 102 B, p. 117).

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